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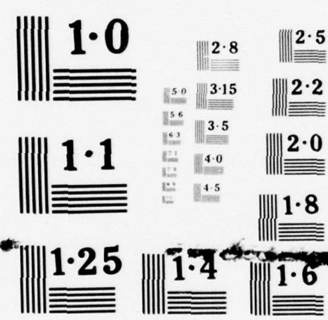

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PROJECT SQUID

SEMI-ANNUAL PROGRESS REPORT

1 APRIL 1977

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Project SQUID is a cooperative program of basic research relating to Jet Propulsion. It is sponsored by the Office of Naval Research and is administered by Purdue University through Contract N00014-75-C-1143, NR-098-038.

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A COOPERATIVE PROGRAM OF FUNDAMENTAL RESEARCH
RELATED TO JET PROPULSION
OFFICE OF NAVAL RESEARCH, DEPARTMENT OF THE NAVY

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I. AERODYNAMICS AND TURBOMACHINERY

Semi-Annual Progress Report

THREE DIMENSIONAL TRANSONIC FLOWS IN COMPRESSORS AND CHANNELS

The University of Michigan, Ann Arbor, Michigan
Subcontract No. 8960-10

Professor T. C. Adamson, Jr.; Principal Investigator
Professor M. Sichel, Principal Investigator

Introduction

The importance of transonic flow problems in modern, high performance turbomachinery is well established. Moreover, at the recent workshop on Transonic Flow Problems in Turbomachinery,(1) sponsored by Project SQUID, NAV-AIR, and AFOSR, it was further indicated that three-dimensional flow fields are of primary importance. The work described here addresses some of the problems found in such three-dimensional flows.

The main objective of this work is to investigate the use of asymptotic methods in steady, three-dimensional transonic flows in rotors. In order to gain some experience in the problems to be met in the analysis, a model three-dimensional channel flow with an incoming shear flow is being considered first, the idea being to study a flow in which the important features of a rotor flow are retained, but in a simple geometry. Because this is a model problem, the viewpoint has been taken that one is interested in obtaining the key features of the flow field in as simple a manner as possible, but that it is not fruitful to obtain very detailed numerical solutions. The asymptotic methods employed allow one to isolate the various trouble spots in the

solutions found from linear governing equations and to concentrate upon obtaining solutions in these special inner regions.

Discussion

The model problem chosen for study may be interpreted as the flow through a linear cascade with the blades aligned parallel to the incoming flow. The symmetry boundaries upstream and downstream of the blades are replaced by walls, so that the flow field considered is that through a three-dimensional rectangular channel with flow constrictions, corresponding to half blades, on opposite walls. The radial variation of the rotor tangential velocity component is accounted for by consideration of a linear gradient in the velocity entering the channel.

The solutions presented previously for this problem in reference 1, were valid to first order. Second order solutions have also been derived and were used to investigate regions where these solutions, derived from linear governing equations, may not be uniformly valid. The following conclusions were reached.

(1) At the leading and trailing edges of the flow constrictions or blades, even though the flow may be mixed subsonic and supersonic along the span of the blade, linear governing equations hold. Bow shocks, as long as they are oblique waves, are so weak that nonlinear equations are unnecessary.

(2) In the region near the plane of the minimum cross sectional flow area (maximum blade thickness), linear governing equations hold as long as the flow is not close to being choked (average Mach number at the minimum cross-sectional flow area is unity). If the flow is close to being choked, nonlinear governing equations hold in this inner region.

These results have considerable importance insofar as evaluation of analytical solutions for rotor flows, derived from linear governing equations, are concerned.

Presently, flows in which shock waves have formed are under study. Since the shock wave does not fill the whole channel, existing only in the supersonic part of the channel, the calculations are quite different from those done in two dimensional channels.

After completion of the study of flows with shock waves, the effects of staggered blades on the solutions will be investigated.

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AXIAL FLOW FAN STAGE UNSTEADY PERFORMANCE

Applied Research Laboratory
The Pennsylvania State University
P. O. Box 30, State College, Pennsylvania 16801

Subcontract No. 8960-4

Edgar P. Bruce, Principal Investigator

Introduction

The objective of this research is to analyze the time-dependent interaction between the components of an isolated axial flow fan stage and a spatially fixed, circumferentially varying flow field. The major variables are reduced frequency; rotor blade space-to-chord ratio, stagger angle, mean angle of attack, and design loading level; and rotor-stator axial spacing.

The experiments are being conducted in the ARL Axial Flow Research Fan (Reference 1). This facility has a hub radius of 12.06 cm (4.75 inches), a hub-to-tip radius ratio of 0.442, and operates in the subsonic incompressible flow regime. The rotor and stator blades have a 10 percent thick C1 profile with a chord of 15.24 cm (6.00 inches) and an aspect ratio of unity.

Instrumentation available at present or under development consists of: (1) a strain gaged sensor mounted within one rotor blade which detects the time-dependent normal force and pitching moment developed on a mid-span blade segment, (2) hot film sensors mounted on the suction surface of rotor and stator blades which detect the nature of the boundary layer, i.e., whether the instantaneous boundary layer flow is laminar, turbulent or separated; (3) dynamic total head probes; (4) two-element hot film probes; and (5) conventional three-dimensional directional probes. A system is being checked-out at present which will permit on-line

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analyses of all time-dependent signals by a digitizing, phase-lock averaging process.

Discussion

The unsteady normal force and pitching moment results obtained in the initial phase of this program at reduced frequencies from 0.22 to 2.08 were reported earlier (Reference 2). Experiments were conducted during the previous reporting period whose objective was to extend the range of reduced frequencies covered for the uncambered, isolated rotor to a value of 5.0 with variations in space-to-chord ratio ($0.68 \leq S/C \leq 2.03$), stagger angle ($35\ \text{deg} \leq \lambda \leq 55\ \text{deg}$) and mean angle of attack ($0 \leq \bar{\alpha} \leq 8$ deg). Analysis of this data showed that the static sensitivity of the sensor employed in these tests was too low to permit an acceptably accurate definition of the unsteady force and moment coefficients. Consequently, a new sensor has been designed with greatly increased static sensitivity, obtained by employing aluminum rather than stainless steel and by employing dynamic strain gages instead of conventional strain gages, at the expense of dynamic performance as measured by an acceptable reduction in natural frequency. This new sensor is being prepared for calibration at present. When this sensor has been calibrated, the uncambered, isolated rotor tests at reduced frequencies from 2.0 to 5.0 will be repeated, and tests to compare cambered (λ=50.3 deg) and uncambered (λ=45 deg) performance in uniform and distorted inflows with $S/C=0.90$ and $\bar{\alpha}=0$ and 8 deg will be conducted (see Reference 3).

The remainder of our effort during this reporting period was devoted toward fabrication and bench testing of the electronic hardware required for surface mounted hot film sensor boundary layer experiments and toward the design and fabrication of a resonant tube device for the calibration

of pressure sensors. Eight hot film anemometers of the type described in Reference 4 were fabricated and used in a shakedown test conducted in a cascade test facility to determine the operational characteristics of the anemometer circuits, the performance of the gages when exposed to laminar, turbulent or separated flow, and the suitability of the proposed AFRF installation on stationary and rotating blades. These tests were successful and plans have been completed for the AFRF installation.

A "Galton Whistle" type standing-wave pressure generator has been designed and fabricted for use in calibrating the dynamic total-head probes required in our future tests. The design of this device was based on the results presented in Reference 5. This device is capable of generating sinusoidal pressures with peak-to-peak amplitudes up to 5 psi at frequencies ranging between 200 and 5000 Hz. This device will be assembled and used in sensor calibrations during the next two months.

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INVESTIGATION OF THE EFFECTS OF HIGH AERODYNAMIC LOADING ON A CASCADE OF OSCILLATING AIRFOILS

United Technologies Research Center
East Hartford, Connecticut 06108
Subcontract 8960-19

Franklin O. Carta, Principal Investigator
Arthur O. St. Hilaire, Principal Investigator

Introduction

The basic objective of this research program is to study the phenomenon of dynamic stall on a cascade of oscillating airfoils. Measurements are being made of the unsteady chordwise pressure distribution, and efforts are being made to detect the occurrence of boundary layer transition and separation on the surface of an oscillating cascaded airfoil operating near the static stall condition.

Program Review

Very little additional progress has been made under the SQUID portion of this program during the past 6 months. Physical receipt of the fully executed contract renewal was not received until early this year, and the test facility was being used for other programs.

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In a related program sponsored by AFOSR (through P&WA) a similar experiment was performed at fixed velocity and incidence angle over a modest range of frequencies and over an extensive range of interblade phase angle, from $\sigma = -60^\circ$ to $+60^\circ$. These data have not yet been fully reduced but our preliminary examination confirms and strengthens our previous finding that interblade phase angle has a very profound effect on the aerodynamic response of the airfoil. Additional tests will be performed later this year under our SQUID contract to extend our knowledge over the same frequency and interblade phase angle range for other incidence angles.

Publication

The following paper was presented at the ASME Gas Turbine Conference, 31 March 1977, Philadelphia, Pa.: Carta, F. O. and A. O. St. Hilaire: Experimentally Determined Stability Parameters of a Subsonic Cascade Oscillating Near Stall. ASME Paper No. 77-GT-47, March 1977.

INVESTIGATION OF ADVERSE PRESSURE GRADIENT CORNER FLOWS

University of Washington, Seattle, Washington
Subcontract No. 8960-27

Professor F. B. Gessner, Principal Investigator
Mr. S. Ono, Research Assistant

Introduction

This research program is an experimental study of incompressible boundary layer development along a streamwise corner in the presence of adverse pressure gradients. The data are intended to provide detailed information on the flow structure in the vicinity of a corner when the flow is decelerating. Both non-separating and locally-separated corner flows are being considered. The data will be compared with numerical predictions based on turbulence models now under development. The measurements will also be analyzed in order to define adequate separation criteria for the corner region.

Within the past few years, various Reynolds stress models have been formulated for turbulent flow along a streamwise corner. These models are based either on length-scale concepts [1,2] or include transport effects in their formulation [3-5]. Both methods of closure have their relative advantages and disadvantages. Length-scale modeling results in a set of algebraic stress equations and relatively short computational times, whereas transport equation modeling is more costly, but involves less empiricism. Although a length-scale model may be appropriate for favorable pressure gradient corner flows, which appear to be in local equilibrium [6], it is likely that a transport-equation type model will be needed for decelerating corner flows, especially for corner flows near incipient separation. It is the intent of the present study to examine the range of applicability and limitations of each type of model for adverse pressure gradient flow conditions. This will be done by means of comparisons with a set of comprehensive data that will be obtained in our laboratory during the present contract period.

Discussion

Our overall corner flow research program is currently being sponsored by a grant from the National Science Foundation and a contract with Project SQUID. That portion of our work supported by Project SQUID is oriented toward obtaining corner flow data under adverse pressure gradient flow conditions. For this purpose, an 8:1 inlet aspect ratio wall-jet diffuser used in a previous study [7] has been modified to provide continuous (step-free) diverging walls. In performing the modification, the flexibility of being able to set the included angle between these walls to any value from 0 to 30 deg has been retained. The traversing mechanism used in the previous study is now being modified to facilitate measurements in the near corner region. The control unit for the axial flow, variable-speed fan is also being modified in order to provide a more precise degree of control on bulk flow conditions.

In anticipation of fairly moderate secondary flows (approximately 10 per cent of the local primary flow) for corner flow conditions near incipient separation [8], response equations have been developed which will permit the Reynolds stress components to be extracted from hot-wire measurements when the wire is subject to additional cooling by a transverse mean flow. It is our present intent to measure the longitudinal normal stress component by means of a normal wire and the remaining (five) stress components by rotating a single inclined wire. This technique has proven to be a reliable means of measuring all six components of the Reynolds stress tensor [9].

Before measurements are made under adverse pressure gradient flow conditions, the limitations of the response equations noted above will be examined by means of measurements in fully-developed pipe flow. In this series of experiments, turbulent shear stress measurements will be made with an inclined wire probe which is offset from the radial direction by fixed degree increments ranging from 0 to 20 degrees. These orientations will induce an apparent secondary flow parallel to the probe stem. Stress components measured relative to coordinate axes parallel and normal to the probe stem will then be converted into stress components referred to pipe flow coordinates. These results will provide useful information on the limitations of the response equations before these equations are actually applied to measurements in the diffuser.

During the present contract period, a three-dimensional k-ϵ turbulence model for turbulent corner flow has been formulated. The appropriateness of this model (and its associated near-wall boundary conditions) will be analyzed as soon as data are available from measurements in the diffuser. The relative merits of this model in comparison to those of a previously formulated length-scale model [1,2] will also be examined.

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TRANSITORY STALL IN DIFFUSERS

Thermosciences Division
Department of Mechanical Engineering
Stanford University
Stanford, California 94305
Subcontract No. 8960-24

Professor James P. Johnston, Principal Investigator
Professor Stephen J. Kline, Principal Investigator
Mr. Jalal Ashjaee, Research Assistant
Mr. John Eaton, Research Assistant

Introduction

The general goal of this program is to study the transitory stall flow regime in two-dimensional diffusers. Maximum value of pressure recovery at fixed non-dimensional length, an important design optimum [1], generally occurs when the turbulent boundary layers are starting to separate or stall. The flow is rather unsteady and significant amounts of transient back flow already are seen in the diffuser at peak pressure recovery. These flow conditions are associated with the onset and development of the transitory stall flow regime [2].

Ghose and Kline [3] have developed a new, steady flow boundary layer prediction method which is solved simultaneously (not iteratively) with the inviscid core flow. This method gives surprisingly good agreement with data on pressure recovery up to, and slightly beyond the condition of peak recovery. The existing wall pressure data in this region are not of sufficient accuracy to properly check the method, however.

The primary objectives of our program are (i) to provide new mean and fluctuation velocity and pressure data in diffusers operating close to peak pressure recovery in order to complement, check, and provide a data base of sufficient accuracy to allow for possible improvement of the prediction method of Ghose and Kline [3], and (ii) to study the magnitude of the velocity and pressure fluctuations in the transitory stall regime in order to provide a useful extension of the work of Smith and Kline [2] and Layne and Smith [4].

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Discussion

Work is proceeding in two areas, (i) the design and construction of a new diffuser wind tunnel and (ii) the investigation of methods for measurement of mean and fluctuating velocities and the Reynolds stresses in, and near, the zone of instantaneous flow separation.

The Diffuser Tunnel. Laboratory space has been prepared for the installation of the new tunnel and the preliminary design is complete. Fig. 1 shows the diffuser mounted in a closed circuit wind tunnel, a configuration chosen because it permits better control of dirt when measurements are made with hot-wire anemometers. An open return configuration will also be possible by removal of the exit plenum from the circuit. A low noise, airfoil bladed centrifugal fan has been ordered. It will operate in a stable range and be of sufficient capacity to drive diffuser inlet speeds up to 150 ft/sec. The fan is to be powered by a DC motor which will be controlled by a very stable feedback system. The control system allows constant speed operation at any selected speed.

The diffuser walls are to be 45 inches long so that the length to width ratio (N/W_1) will be approximately 15:1. When the inlet nozzle is set to an inlet width of 3 inches, the aspect ratio of the diffuser will be 4:1, sufficiently large to reduce end-wall effects to a small, tolerable level. The side walls of the diffuser will have short, flexible sections at both inlet and outlet planes, so that 2θ may be adjusted to arbitrary angles up to approximately 24°. The small changes in axial length that accompanies variation of wall angle will be accommodated by short parallel side-wall segments at the diffuser exit plane. These segments will be free to slide through a rectangular, adjustable hole in the upstream wall of the exit plenum box. The diffuser walls will be made of half inch thick plexiglass to allow for flow visualization.

The upstream nozzle and screen assembly already exists. A new honeycomb made of plastic soda straws packed in close array will be set ahead of the upstream screen. The screens and honeycomb were designed following recommendations found in the current literature and the design appears to be more than adequate to assure very low turbulence inlet flow with a flat velocity profile at diffuser entry.

The tunnel is designed so that the fan, the motor and the return circuit will be permanently fixed relative to the laboratory floor. Ducts in lengths up to 8 feet may be inserted between the honeycomb and the heat exchanger in order to accommodate various lengths of inlet duct between the nozzle and the diffuser and/or exit tail pipes.

Measurement Techniques. We are currently surveying a number of candidate techniques for the measurement of velocity in the flow separation zone. Among those under consideration at the present time are:

(1) A hot-wire anemometer with an additional thermal sensor wire to indicate the presence or absence of the wake of the hot-wire. Forward and reverse directions are thereby obtained in addition to instantaneous velocity magnitude.

(2) A hot-wire probe that may be moved at a known velocity relative to the flow field to cause all velocities sensed by the probe to be positive, this is the so-called flying hot-wire method.

(3) The laser velocimeter with frequency shifting to cause all apparent velocities to be positive.

(4) The pulsed-wire anemometer, an instrument that senses velocity, magnitude and direction by a time of flight technique.

We have decided not to employ techniques (2) and (3) primarily for reasons of mechanical complexity and cost. Method (1) is being pursued, but will require considerable development and very careful calibration in separated flows. The pulsed wire technique (4) can be used to check work on method (1) and can also be used directly to study reattachment and separation of turbulent shear layers.

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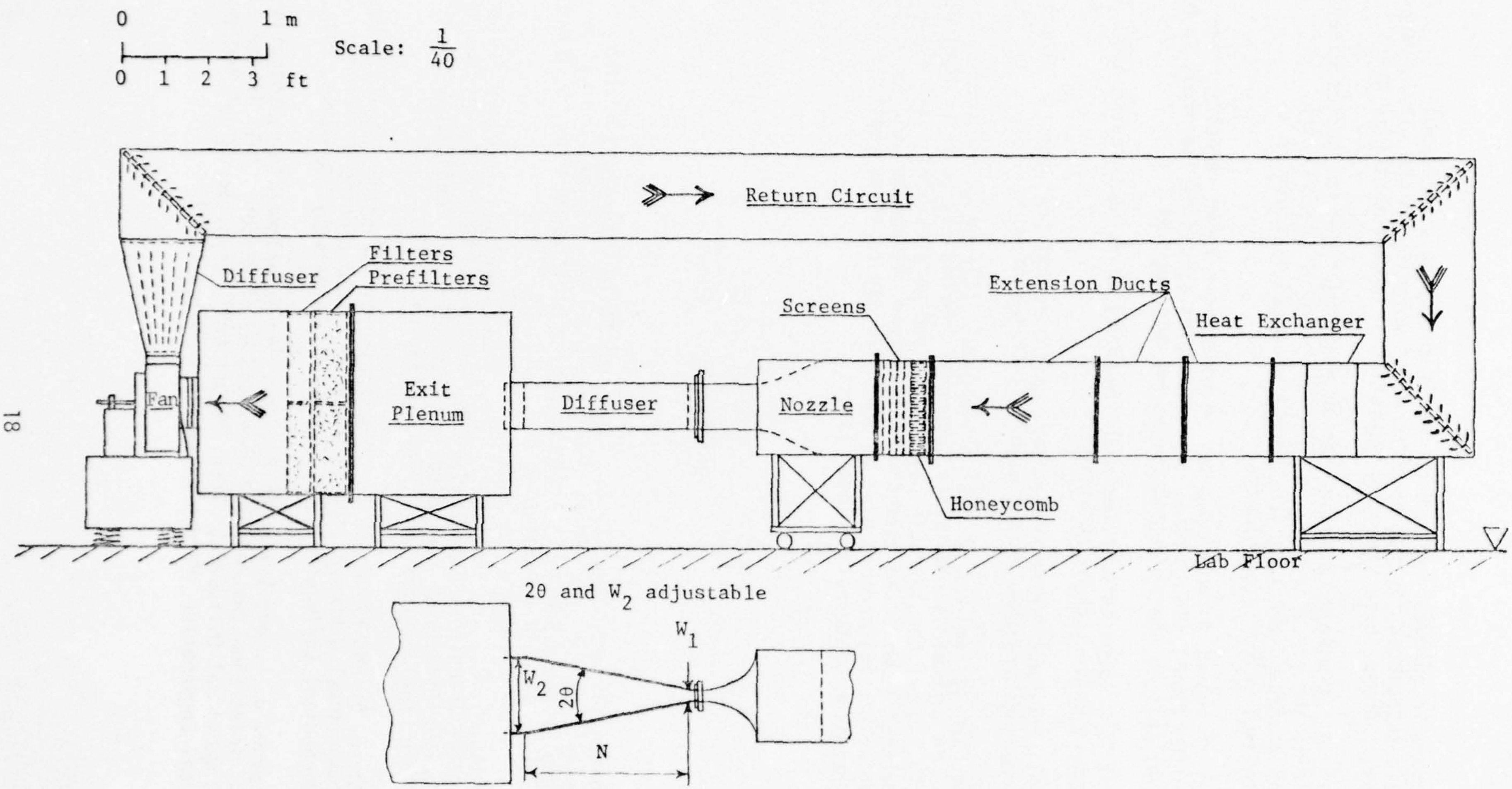

Fig. 1. Diffuser test apparatus

JA/JPJ
March 1977

AN INVESTIGATION OF PRESSURE FLUCTUATIONS AND STALLING CHARACTERISTICS ON ROTATING AXIAL-FLOW COMPRESSOR BLADES

Virginia Polytechnic Institute
and State University, Blacksburg, Virginia
Subcontract No. 8960-13

Professor H. L. Moses, Principal Investigator
Professor W. F. O'Brien, Jr., Principal Investigator
Mr. R. R. Jones, Research Assistant
Mr. C. T. Jones, Research Assistant

Introduction

This research is intended as a contribution to a better physical understanding and prediction of the stalling behavior of axial-flow compressors. The compressor characteristics of interest include the loss in performance and the instabilities associated with stall. Both experimental and analytical efforts are included in the research program.

The primary objective of the experimental effort is to obtain direct on-rotor flow data, as well as data from the stationary components of the compressor, for flow conditions up to and during stall. Since instrumentation for on-rotor measurements has been inadequate, especially for high-frequency response, much of the initial work on the program was devoted to the development of a telemetry data transmission system and blade-mounted pressure transducers.

Much of the experimental work is being conducted on a relatively low-speed (~ 2400 RPM), one- or two-stage axial-flow compressor. This

facility allows a basic investigation of the stalling behavior with a minimum of on-rotor instrumentation difficulties, and the flow is essentially incompressible. An additional, high-speed (~ 17,000 RPM) compressor research facility has been constructed as a part of the program.

The analytical effort is directed at developing a basic flow model that includes the essential features of the stalling behavior. The model is based on an interaction between an inviscid region and boundary layers on the compressor blades and end walls. Flow separation, three-dimensional effects, and unsteady behavior are approximated in the model.

Discussion

A scanning pressure measurement system was installed on the low-speed research compressor to provide very accurate measurements of average pressure levels. This system was used in previously-reported studies of chord-wise pressures on a rotor blade at three radial stations. The system exibited some capability for dynamic pressure measurements, and an initial study of the frequency content of pressure fluctuations associated with rotating stall induced by loading and distorted inlets was conducted. The rotating stall condition was identified using high response dynamic pressure probes mounted 120 degrees apart at the rotor discharge. These probes replaced the previously-used hot wire probes, and were found to be much more reliable and easier to use. When rotating stall was observed, the frequency signature of the high-response probes showed a strong signal at approximately 1/2 rotor speed. This indication is presently

used for the identification of the stall condition in the low-speed research compressor.

It is planned to return to the use of high response pressure transducers for the study of on-rotor pressure fluctuations, both in the low- and the high-speed facilities. The degree of cross correlation of the on-rotor transducer signal with the rotor-downstream mounted probes is of interest, and experiments to establish the technique are in progress. As would be expected, correlograms show positive results at multiples of approximately one-half rotor frequency when rotating stall is present.

A microcomputer has been obtained for use in data acquisition in the turbomachinery laboratory. Currently, initial programming and instrument system design are underway. This system will provide for rapid digital processing of pressure fluctuation and other signals.

The state-of-the-art compressor research facility, which is capable of rotational speeds up to 24,000 RPM, was completed during the past year. Initial operation of the gas turbine drive engine was quite successful over its complete range. The research compressor, however, developed an excessive run-out at the design speed. A new research compressor, which is similar to the old one, has been obtained and is currently being installed. The complete facility is described in Ref. 1. Future plans for the high-speed facility include a detailed experimental determination of the stalling characteristics of the research compressor and on-rotor experiments involving a single blade-mounted pressure transducer and strain gauges.

Much of the analytical effort on the program has been devoted to the calculation of separated, or stalled, flow. A procedure for

simultaneously calculating the inviscid flow region and the boundary layers, including separation, has been developed, and a report of this work is being prepared. Progress has been made in relating the flow turning angle, or work, and the loss of performance to the boundary layer growth. An approximate correction for the effect of end-wall boundary layers has also been developed. Thus, an analytical model for the quasi-steady behavior of the low-speed compressor up to stall is near completion, and an approximation for the unsteady effects is in progress. Both quasi-steady and unsteady models will be compared with the experimental results. Future plans include the addition of compressible flow effects in the analytical model and comparison with experimental results from the high-speed facility.

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Semi-Annual Progress Report

EFFECTS OF TURBULENCE ON FLOW THROUGH AN AXIAL COMPRESSOR BLADE CASCADE

Colorado State University, Fort Collins, Colorado
Subcontract No. 8960-15

Professor Willy Z. Sadeh, Principal Investigator

Introduction

The long-term objective of this research program is to ascertain the role which oncoming turbulence can play in reducing the aerodynamic losses in flow through a blade cascade of an axial-flow compressor at moderate Reynolds numbers of order of 2×10^5 or smaller. At these Reynolds numbers prohibitively high losses and even fully stalled blades are induced by laminar separation of the profile boundary layer. Supply of oncoming turbulence of sufficient energy concentrated at scales commensurated with the thickness of the prevalent profile boundary layer can forestall the laminar separation. Suitable management of the turbulent energy distribution possesses, furthermore, the potential to even generate and sustain a fully attached turbulent boundary layer on the profile suction side. Accumulation of turbulent energy at the scales of interest can be produced by the selective amplification of turbulence. This selective turbulent energy intensification is governed by the vortex stretching mechanism characteristic to forward stagnation flow.

Discussion

The investigation is divided into three phases of augmenting

complexity for the sake of securing its successful completion. In all these three stages the evolution of the oncoming turbulent energy, its selective amplification and, finally, its effects on the body boundary layer are to be studied. The bodies to be utilized are: (1) a circular cylinder in the first phase; (2) an isolated airfoil in the second stage; and, (3) a stationary blade cascade in the last phase.

The preliminary limited task planned for the current year has almost been completed. This effort has been geared toward laying down all the necessary provisions for consummating the first two phases within one single year at reduced cost. The circular cylinder (Phase I) and the turbulence-generating grid are constructed and ready for use. A single airfoil (NACA 65-010) of 122 cm (4 ft) chord was designed and it is being built (Phase II). In addition, two more single airfoils (NACA 65-608 and 65-612) are currently being conceived (Phase II). All the measuring instrumentation including six hot-wire anemometers have been checked and are fully operational. The needed programs for data reduction have been tested. As a matter of fact, most of the background work required to accomplish the goals of the first two phases during the forthcoming year have been met.

The exploratory effort regarding the matching of the outer and inner solutions of the vorticity amplification theory has been further pursued. Several numerical schemes for carrying out the matched asymptotic expansions are still being inspected and tested. Apparently, a composite expansion can lead to a reasonable approximation concerning the supply of amplified turbulent energy to the body boundary layer.

FUNDAMENTAL RESEARCH ON ADVERSE PRESSURE GRADIENT INDUCED TURBULENT BOUNDARY LAYER SEPARATION

Southern Methodist University, Dallas, Texas
Subcontract No. 8960-25

Professor Roger L. Simpson, Principal Investigator
Mr. C. R. Shackleton, Research Assistant

Introduction

The problem of turbulent boundary layer separation due to an adverse pressure gradient is an important factor in the design of many devices such as jet engines, rocket nozzles, airfoils and helicopter blades, and the design of fluidic logic systems. Until the last three years little quantitative experimental information was available on the flow structure downstream of separation because of the lack of proper instrumentation.

In 1974 after several years of development, a one velocity component directionally-sensitive laser anemometer system was used to reveal some new features of a separating turbulent boundary layer [1]. The directional sensitivity of the laser anemometer system was necessary since the magnitude and direction of the flow must be known when the flow moves in different directions at different instants in time [2]. In addition to much turbulence structure information, it was determined (1) that the law-of-the-

wall velocity profile is apparently valid up to the beginning of intermittent separation; (2) that the location of the beginning of intermittent separation or the upstreammost location where separation occurs intermittently is located close to where the freestream pressure gradient begins to rapidly decrease; (3) that the normal stress terms of the momentum and turbulence kinetic energy equations are important near separation; and (4) that the separated flowfield shows some similarity of the streamwise velocity U, of the velocity fluctuation u', and of the fraction of time that the flow moves downstream [3].

Based upon these results, modifications [4] to the Bradshaw, et al. [5] boundary layer prediction method were made with significant improvements. However, this prediction effort pointed to the need to understand the relationship between the pressure gradient relaxation and the intermittent separation region structure. Another limiting factor for further refinement of the prediction of separated flows is the lack of fundamental velocity and turbulence structure information, especially in the backflow region. Thus, the objective of the current research program is to provide this information by using a directionally-sensitive laser anemometer system to determine quantitatively the turbulence structure of a separating, separated, and reattached turbulent boundary layer.

Discussion

This current research program was begun October 1, 1976, to obtain laser anemometer measurements of the separating flow of an adverse pressure gradient turbulent boundary layer for an airfoil or cascade blade type pressure distribution. Considerable effort has been made to avoid mean flow three-dimensionality. Specially designed wall suction and tangential wall jet boundary layer controls and peripheral equipment have been installed into the wind tunnel test section and are being tested. The flow produced by these controls is two-dimensional within 1%. Further refinements to the laser anemometer system have been made to improve signal quality. The new direct digital computer system for acquisition and analysis of turbulence data is nearing completion.

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II. COMBUSTION AND CHEMICAL KINETICS

A SHOCK TUBE STUDY OF H_2 AND CH_4 OXIDATION WITH N_2O AS OXIDANT

University of Missouri, Columbia, Missouri
Subcontract No. 8960-21

Prof. Anthony M. Dean, Principal Investigator
Dr. Edward E. Wang, Research Associate
Mr. Don C. Steiner, Research Assistant

Introduction

The study of oxidation reactions in shock tubes has been stimulated by the advent of fast, accurate numerical integration routines. No longer tied to the steady state approximation, kineticists can more definitely test various oxidation mechanisms by a detailed comparison of calculated and observed concentration-time profiles. Unfortunately, application of this approach to even such "simple" systems as $CH_4/O_2/Ar$ is severely limited by the lack of reliable rate constant data at higher temperatures--the number of variables is simply too large. Recent work in this laboratory (1-3) has demonstrated that N_2O is a particularly useful precursor of oxygen atoms. These observations suggested that the study of oxidation reactions where N_2O replaced O_2 as oxidant might provide useful information about the rate of reactions of atomic oxygen with various molecules at high temperatures. The use of N_2O as an oxidant has several advantages; the most significant is that oxygen atom reactions will occur in an environment substantially free of O_2. Successful completion of the N_2O studies would then permit one to approach the CH_4/O_2 system with prior knowledge of the rates of the oxygen atom reactions to be encountered there. This reduction in the number of unknown variables should then allow for much more incisive testing of the oxidation mechanism.

Our first efforts in this program utilized hydrogen as the fuel molecule. Unlike the case of methane, the H_2/O_2 system has been well characterized and the rate constants for the individual reactions are reasonably well known (4). Thus, we can use this system as a "calibration" device; analysis of the $N_2O/H_2/CO$ system should yield values of $O + H_2 \rightarrow OH + H$ in good agreement with those obtained from more traditional studies. Agreement of our results with the literature here would suggest that future work on systems containing hydrocarbons should yield equally reliable results. Furthermore, the hydrogen system allows us to determine the kinetic influence of the added CO. (CO must be added to observe the flame-band emission which is our method for monitoring atomic oxygen). The $H_2/O_2/CO$ system has been studied quite extensively (5,6) and our observations with different amounts of

added CO can be checked against the earlier work. With this information in hand, one is in a much more secure position to consider the methane system. We are particularly interested in methane since this fuel is of such importance in practical combustion systems. Also it is clear that many of the details of the combustion of more complex hydrocarbons will be similar to that in methane; successful analysis of the methane case will simplify future analyses of these fuels.

Discussion

During the last six months, we have been able to complete our studies of the H_2 system with both O_2 and N_2O as oxidants. We have measured absolute oxygen atom and carbon dioxide concentration-time profile for mixtures containing 1% O_2, 0.05% H_2 and either 3% or 12% CO in Ar. Experiments were performed between 2000 and 2800°K, and both infrared (CO_2) and visible (O) signals were quantitatively corrected for background emissions. Calculated profiles were obtained using the accepted mechanism (5,6) and consensus rate constants for these reactions. Such profiles are in remarkably good agreement with all of the observations in this system. In particular, the flame-band data shows excellent agreement in terms of induction times, exponential growth rates, and "equilibrium" values for oxygen atom production. Likewise, all aspects of the observed CO_2-time behavior are in good agreement with those calculated. The extent of the agreement is particularly gratifying since it serves to confirm the validity of our experimental technique. In particular, it serves as a check on our calibration procedures which allow us to assign absolute oxygen atom and carbon dioxide concentrations from the measured (corrected) signals.

We have performed this same sequence of experiments with 1% N_2O substituted for 1% O_2. Here comparison of observed and calculated concentration-time profiles have allowed us to determine a high temperature rate constant for the reaction $H + N_2O \rightarrow N_2 + OH$. With this value, it was observed that agreement of all of our data for both oxygen atom and carbon dioxide production was comparable to that achieved for the O_2 system. The N_2O system appears to be behaving as we predicted. This sequence of experiments has served three purposes: (1) It suggests that our approach to the study of oxygen atom kinetics is valid; the oxygen atom profiles in the N_2O system are in accord with that predicted by the "known" rate constant for $O + H_2 \rightarrow OH + H$. (2) These experiments have allowed the rate constant for $H + N_2O \rightarrow N_2 + OH$ to be determined in the high temperature regime where there had been considerable uncertainty. (3) This combination of rate constants can now be carried over to the methane system; the only unknowns in that system will be the rate constants for the reactions of interest.

In light of the success achieved in the H_2 system, we have initiated our experiments with methane. Data to date have shown that the background emissions in the methane system are appreciably smaller than we feared. As a result, we are able to collect flame-band data at the same wavelength used for the hydrogen work. This means we will not have

to perform a long, laborious search for some new spectral region. Preliminary numerical calculations have been done on this system. Comparison of these profiles to those observed suggest that this system is behaving as expected. It is premature to report values for the rate constant of the reaction $O + CH_4 \rightarrow CH_3 + OH$, but the consistency of the data suggest that such a value will be forthcoming.

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COMBUSTION KINETICS AND REACTIVE SCATTERING EXPERIMENTS

Yale University, New Haven, Connecticut
Subcontract No. 4965-16

J.B. Fenn, Principal Investigator
N. Abuaf, B. Halpern and M. Labowsky

Introduction

The combustion of hydrocarbon fuels has been man's most used source of useful energy for much of this century. The chemical reactions which it involves have been among the most studied. And yet, there remains uncertainty as to the nature of the first reactive step in the complex sequence of reactions by which oxygen and hydrocarbon molecules become hot combustion products. This investigation comprises an attempt to identify that first reactive event and to determine its cross section by means of molecular beam scattering methods. The prospective advantage of such methods is that they can examine the consequences of a single collision between individual molecules. By the same token they are substantially limited in their ability to probe intermediate reaction steps which involve species of transient existence such as free radicals not readily obtainable as beams. In addition to this new venture in combustion kinetics we have been continuing a study of the evaporation and combustion of arrays of droplets. This study is based on an adaptation of the

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method of images which has been successful in solving Laplace's equation as it applies to electrostatic problems involving arrays of charged particles.

Discussion

A. Reactive Scattering. The cross sections of the first reactive steps in the combustion process are probably substantially smaller than those for which molecular beam methods have thus far been most effective. Consequently, we must achieve much higher detection sensitivities than have been usual in molecular beam experiments. Our approach is to employ uncollimated beams comprising free jets from small sonic nozzles exhausting into an evacuated region. The idea is to oppose a jet of hydrocarbon molecules with a jet of oxygen molecules. After collision the molecules and any product species will be trapped cryogenically or on adsorbents. Collection will continue for suitably long periods of time. Then the reaction chamber will be isolated and heated so that the trapped species return to the gas phase and can be swept out by a stream of helium for analysis by gas chromatography. We have already used variations of these techniques with some success in the study of molecule surface reactions and in molecular energy transfer during gas-gas molecular collisions at high velocity. The new feature is the trapping and collection of product flux for subsequent analysis.

Thus far in this new program we have built the reaction system. It comprises a pair of nozzle sources heated electrically and

separated from the reaction zone by cooled radiation shields so that no hot surfaces will be accessible by reactant molecules after they issue from their source nozzles. These two nozzles are 30 μm in diameter and oppose each other at distances variable up to about four inches in a circular reaction chamber 15 cm in diameter and 20 cm high which is evacuated by a four inch diffusion pump. Between the reaction chamber and the pump are a four inch valve and a trap which can be pumped on the liquid nitrogen side so as to achieve temperatures as low as the freezing point of nitrogen, 63.3 K. By our calculations this temperature will be low enough to trap cryogenically any hydrocarbons containing three or more carbon atoms and their likely initial products. At this writing we are about to make some tests of trapping effectiveness and analysis techniques by some blank runs in which mixtures of known composition will be introduced through the nozzles.

B. Behaviour of Particle Clouds. The method of images has been further extended to treat arrays of up to 20 particles of varying size in random configurations. In an interesting particular case the method was applied to the combustion of a cloud of droplets of equal size. It was found that at droplet separations up to thousands of droplet diameters the cloud burned in a group mode as though it were a single large drop. At such large separations the images method consumes substantially less computer time because only a first iteration is required. Consequently, it was possible to treat an array of 729 droplets. The results were in remarkable

agreement with results obtained by drawing on an analogy to the well known problem of reactant diffusion through a porous catalyst pellet. The noteworthy conclusion is that rarely in practical combustion systems will one encounter conditions in which combustion occurs as an aggregate of separately burning droplets each with its own diffusion flame. More often clouds of droplets will behave as a large pocket of vapor burning in an extended peripheral diffusive flame. A paper describing this study will be included in the _Proceedings of the Symposium on Evaporation and Combustion of Fuel Droplets_ to appear in a volume of the American Chemical Society's _Advances in Chemistry_, now in press.

HIGH-TEMPERATURE FAST-FLOW REACTOR CHEMICAL KINETICS STUDIES

AeroChem Research Laboratories, Inc., Princeton, NJ 08540
Subcontract 8960-16

Arthur Fontijn, Principal Investigator
William Felder, Physical Chemist
James J. Houghton, Research Associate

Introduction

Reliable quantitative knowledge of the kinetics of free metal atom and metal oxide species is required for a better understanding and description of (i) the burning of metallized propellants and (ii) the exhaust properties of rockets using such propellants. Suitable techniques for obtaining such kinetic information were unavailable until we adapted the tubular fast-flow reactor technique to reach temperatures up to 2000 K (1). This development has extended an essentially room temperature technique to being capable of being used for making measurements in the temperature range of conventional high-temperature techniques such as flames and shock tubes.

The agreement between (extrapolated) rate coefficients obtained from high and low temperature determinations by separate techniques is often poor. It is also becoming apparent that, for many reactions, Arrhenius-type plots of rate coefficients vs. T covering ranges on the order of 1000 K or more show distinct upward curvature with increasing T (e.g. Refs. 2,3), thus making extrapolation of k(T) data over wide temperature ranges

a procedure of doubtful validity. For reliable k(T) measurements it is desirable to use a single technique to span the entire T-range of interest. For the 300-2000 K range our high-temperature fast-flow reactor (HTFFR) technique provides such a technique for the first time.

Discussion

In the report period we (i) completed our measurements on the reaction

$$Al + CO_2 \rightarrow AlO + CO \qquad [1]$$

(ii) submitted a paper discussing the results (4), and (iii) performed work on the reaction

$$Al + SO_2 \rightarrow AlO + SO \qquad [2]$$

Over the 310-730 K range the rate coefficient $k_1(T)$ of Reaction [1] obeys an Arrhenius expression, with an activation energy $E_A[1]$ of 2.6 ± 1.3 kcal mole^{-1}. Above 730 K, $k_1(T)$ increases much more rapidly with T. This is apparently the first experimental evidence for such non-Arrhenius behavior in a metal oxidation reaction. This behavior of Reaction [1] cannot be described on the basis of simple transition state theory alone; the most probable additional factors involved are the opening up of a second reaction channel leading to $AlO(A^2\Pi)$ and preferential reaction of Al with CO_2 in bending modes (4).

The above value of $E_A[1]$ implies $D(Al{-}O) \geq 123.7 \pm 1.3$ kcal mole^{-1}. The lower limit value of 122.4 is equal to the maximum value given by JANAF (5), $D(Al{-}O) = 120 \pm 2$, and casts some doubt on this usually accepted $D(Al{-}O)$. Since the value of this bond energy is important for accurate

predicting and modeling of rocket exhausts using aluminized solid propellants, it appears important to investigate this point further, for which purpose Reaction [2] was selected. (The O—SO bond strength is 132 kcal mole^{-1}, 6 kcal mole^{-1} more than the O—CO bond strength (5).) Thus far we have made 24 individual k_2 measurements (over a wide range of pressures, flow velocities and Al-concentrations), centered mainly around 700 and 1600 K. If we assume for purposes of calculation that Reaction [2] follows Arrhenius behavior then we obtain from these measurements

$$k_2(T) = (3.4 \pm 1.2) \times 10^{-10} \exp[(-2850 \pm 300)/T] \qquad [3]$$

which indicates $D(Al—O) \gtrsim 126$ kcal mole^{-1}. However, if this reaction has non-Arrhenius behavior similar to Reaction [1] then a lower $E_A[2]$ and hence higher D(Al—O) might be indicated. Thus it is now necessary to perform experiments at intermediate temperatures.

The preliminary results given by Eq. [3] suggest some interesting conclusions:

(i) The pre-exponential is some three orders of magnitude higher than that for Reaction [1] at "low" (310-730 K) temperatures. This may be due to the fact that SO_2 and SO_2^- have similar bent structures, allowing Reaction [2] to proceed by an electron jump (harpooning) mechanism. Such a mechanism cannot occur in the Al/CO_2 reaction with ground state CO_2 (CO_2 is linear, CO_2^- bent) but can occur at higher temperatures with CO_2 in bending modes (4). A similar explanation has been suggested by Smith and Zare (6) for the factor of 4 increase in the cross section of the spin-forbidden Ba/SO_2 reaction

relative to the spin-allowed Ba/CO_2 reaction. (The larger difference in the pre-exponentials of Reactions [1] and [2] may be due to the fact that both these reactions are spin-allowed.)

(ii) The indicated D(Al—O) would imply that Reaction [1] is not endothermic and hence that its energy barrier (activation energy) is due to other factors, e.g., its inability to proceed by an electron jump mechanism with ground vibrational state CO_2.

(iii) It should be noted that we previously found that the Al/O_2 reaction which is both exothermic and can proceed via an electron jump mechanism is fast ($k = 3 \times 10^{-11}$ ml molecule^{-1} sec^{-1}) and has no measurable activation energy over the 300 to 1700 K range (7). Electron jump considerations thus may be quite important in predicting reaction rate coefficients even for Group III metals.

Lectures

The Principal Investigator presented talks on our Project SQUID work at Cornell University and at Brookhaven National Laboratory.

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EXPERIMENTAL AND THEORETICAL STUDIES OF MOLECULAR COLLISIONS AND CHEMICAL INSTABILITIES

Massachusetts Institute of Technology, Cambridge, Massachusetts
Subcontract No. 4965-10

Professor John Ross, Chief Investigator
Dr. I. Procaccia
Mr. Randolph Burton

Introduction

The research program is concerned with theoretical and experimental studies of molecular collisions in reactive and non-reactive systems, and theoretical and experimental studies of chemical instabilities.

Discussion

A. Chemical Instabilities. We are continuing our work on chemical instabilities in the system NO_2, N_2O_4 irradiated by an argon ion laser. In previous work we have shown that the system is subject to instabilities in that it shows multiple stationary states and chemical hysteresis.

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The transition from one branch of stable states to another does not occur homogeneously but occurs by a nucleation process. We are setting up an experiment in which we intend to measure spatial and temporal autocorrelation functions to provide information on far-from-equilibrium fluctuations and details of nucleation processes. To do the experiment we have purchased from separate funds an optical multi-channel analyzer system which consists of a two-dimensional array of approximately 100,000 photo-sensitive regions each of linear extent of about 100 microns. With this array we shall be able to map the concentration profile of the system due to the natural fluorescence of photo-excited NO_2.

In connection with another set of experiments on reactions of photo-excited NO_2 we have observed an interesting sequence of events in the system consisting of SO_2 and NO_2. On irradiation visible white particles are formed which we believe to be a polymer of SO_2. Under continuous radiation these white particles order themselves in macroscopic spatial structures. The possibility of this kind of behavior was predicted by us theoretically some years ago. The phenomena is quite complex in that in addition to spatial structures, pulsations and waves are also observed. Although all of these events are fascinating it is clear that in order to understand any one of them we must try and separate their appearance as much

as possible. We are in the process of mapping out the behavior of the system with variations in light intensity, mole ratio of concentrations and temperature.

B. Chemical Dynamics. Recently there have appeared a number of experiments on laser induced chemistry in which it was supposed that the initial excitation of the molecule remains localized within the molecule and thus leads to reaction. We have constructed a model in which vibration-vibration energy exchange on collision occurs rapidly so that vibrational modes of the molecule become excited. However, vibration-translation is a slow process and thus the energy flow from molecule to molecule gives rise to a nonstatistical energy distribution (Traynor effect). This nonstatistical distribution can lead to an effective lowering of the measured activation energy. The observed lowering of the activation energy has in our view been wrongly attributed to localization of excitation energy rather than nonequilibrium distributions.

A previously developed approximate theory of chemical dynamics based on generalized Franck-Condon factors was used to study the information theoretical analysis of vibration-rotation distributions and of isotopic branching ratios. We began by examining the surprisal function we obtained from the Franck-Condon factors for rotational and vibrational distributions. For rotational distributions we

found linear surprisal behavior for low rotational excitation in the limit of strong potential and weak kinematic coupling, but nonlinear surprisals for high rotational excitation in that limit. In addition, nonlinear rotational surprisals were generally obtained for any degree of rotational excitation in the limit of strong kinematic and weak potential coupling. We found these generalizations from the Franck-Condon factors and their applications to the $H+H_2$, $F+H_2(D_2)$ and $H+Cl_2$ reactions. For $F+H_2(D_2)$, nearly microcanonical rotational distributions were obtained (for low j'), due to the cancellation of contributions from the angular coordinate overlap factor (which led to a positive slope ("Temperature") parameter θ) and centrifugal stretching effects (which led to negative θ). For vibrational distributions linear surprisals were obtained for $F+H_2(D_2)$ where little of the reaction exoergicity was released in the exit channel and the region of maximum overlap of reagent and product wavefunctions was highly localized, but not for $H(D) + Cl_2$, which had a higher repulsive energy release (in the terminology of Polanyi and coworkers) and a more delocalized overlap. For both rotational and vibrational surprisals, we found that linearity occurred when the potential constrained the reaction to occur through a highly localized set of nuclear configurations (and hence in the limit of strong potential coupling and of highly localized overlaps).

In our study of branching ratios, we considered the isotopic branching in F+HD → FH(FD)+D(H). We first showed that the purely dynamical Franck-Condon factor provided a correct qualitative description of the branching ratio (especially its dependence on reagent rotational excitation). We then used information theory to predict the same ratio, and found some points of similarity to the purely dynamical result (such as the dependence on parameters of the product state distributions), but also certain important points of difference (such as dependence on degree of reagent rotational excitation). These points of similarity and difference may be reinterpreted in terms of the relative contribution of strongly coupled potential and kinematic effects respectively, and the success of simple information theoretic branching ratio predictions depends on the relative importance of these factors.

Publications

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2. "Franck-Condon factors in studies of dynamics of chemical reactions II. Vibration-rotation distributions in atom-diatom reactions," J. Chem. Phys. 66, 1037 (1977). G. C. Schatz and John Ross.

3. "Franck-Condon factors in studies of dynamics of chemical reactions III. Analysis of information theory for vibration-rotation distributions and isotopic branching ratios," Accepted for publication in J. Chem. Phys. G. C. Schatz and John Ross.

4. "On the quasi-adiabatic description of the dynamics of electronically adiabatic chemical reactions," accepted for publication in J. Chem. Phys. Shaul Mukamel and John Ross

5. "On stochastic reductions in molecular collision theory: projection operator formalism; application to classical and quantum forced oscillator model," accepted for publication in J. Chem. Phys. G. C. Schatz, F. J. McLafferty and John Ross

6. "Comment on non-statistical behavior in laser chemistry and chemical activation" accepted for publication in J. Chem. Phys. Shaul Mukamel and John Ross

7. "Formation of ensembles with constraints of coherence," accepted for publication in J. Chem. Phys. Itamar Procaccia, Shaul Mukamel and John Ross

8. "Angular distributions of chemiluminescence from $Ba+Cl_2$," J. Chem. Phys. 66, 1378 (1977). Charles A. Mims and John H. Brophy.

Lectures

The Principal Investigator presented invited lectures at:

IBM Research Laboratories, Yorktown, New York
XVIth Solvay Conference, Brussels
University of Massachusetts, Boston
City College, New York
Joint Physical Chemistry Symposium of California Institute of Technology; University of California, Los Angeles; University of Southern California Los Angeles
Cornell University, Ithaca, New York

A BASIC STUDY ON THE MECHANISM OF INFLAMMABILITY LIMITS AND THE BEHAVIOUR OF NEAR-LIMIT FLAMES

Case Western Reserve University
Cleveland, Ohio
Subcontract No. 8960-2

Professor James S. T'ien, Principal Investigator

This contract was in a no-cost extension status for the past six months. In this period of time, the major task was to prepare an AIAA paper* for presentation in the 15th Aerospace Science Meeting. The paper will appear in a proposed volume on Turbulent Combustion in Progress in Astronautics and Aeronautics Series.

In the above-mentioned paper, the experiments on spontaneous flame oscillation near the extinction limit were described. In addition, a number of other flame pulsation phenomena which were of similar nature (i.e., occuring only near the limit) were compared.

*Chan, W.Y. and T'ien, J.S., An Experiment on Spontaneous Flame Oscillation Prior to Extinction, AIAA Paper No. 77-184.

III. MEASUREMENTS

TURBULENCE MEASUREMENTS
IN JETS FLAMES AND COMBUSTORS

Polytechnic Institute of New York
Aerodynamics Laboratories

Subcontract No. 8960-5

S. Lederman - Principal Investigator

Introduction

In the last semi-annual progress report of September 20, 1976 it was stated that a better utilization of the developed diagnostic techniques required an expansion of the data acquisition and processing equipment. It was further indicated that this expansion was in progress and it should provide the capabilities of obtaining simultaneously temperature and concentration of several species as well as the velocity of the flow. In addition, through the expanded data storage capacity, turbulence intensity, concentration and temperature fluctuation, as well as the mixedness parameters may be obtained, by proper processing of the stored data.

Discussion

Since the inception of the program in our laboratory, dealing with the development of nonintrusive diagnostic techniques applicable to flow fields and combustion, several versions of the apparatus have been constructed, calibrated and applied towards the acquisition of

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data concerning concentration of species (1-6) temperature profiles (3-6) velocity profiles (6-7) and turbulence intensities (7-10). The diagnostic systems consisted generally of different versions of Raman and LDV probes. Recently a CARS system has been added as indicated in the last progress report and in Ref. 11. The Raman probe as used in our laboratory was of the short duration (10-20nsec) high peak power pulse variety, which permitted the acquisition of instantaneous specie concentration and temperature of as many species in a flow field or flame as there are involved, and data acquisition channels available. Recently our data acquisition system has been expanded and calibrated resulting in a diagnostic system capable of handling simultaneously six Raman and one velocity data channels. Thus it it now possible to acquire simultaneously velocity and turbulence information, four specie concentrations, concentration fluctuations and concentration cross correlations or velocity and turbulence intensity, as well as two specie concentrations, their temperatures and concentration and temperature fluctuation. This new system is shown in a diagramatic form in Fig. 1.

Using this sytem, a number of concentration, temperature and velocity profiles have been obtained as shown in the next several figures.

At this time some numerical work is being done in an attempt to correlate some of our experimental work with some available turbulence models of a coaxial turbulent diffusion flame. As far as the CARS

system is concerned, the ruby laser which has been used on this system failed, and this work had to be temporarily halted. However, it is expected to resume this work within about six weeks, after an extensive overhaul of the laser system is completed.

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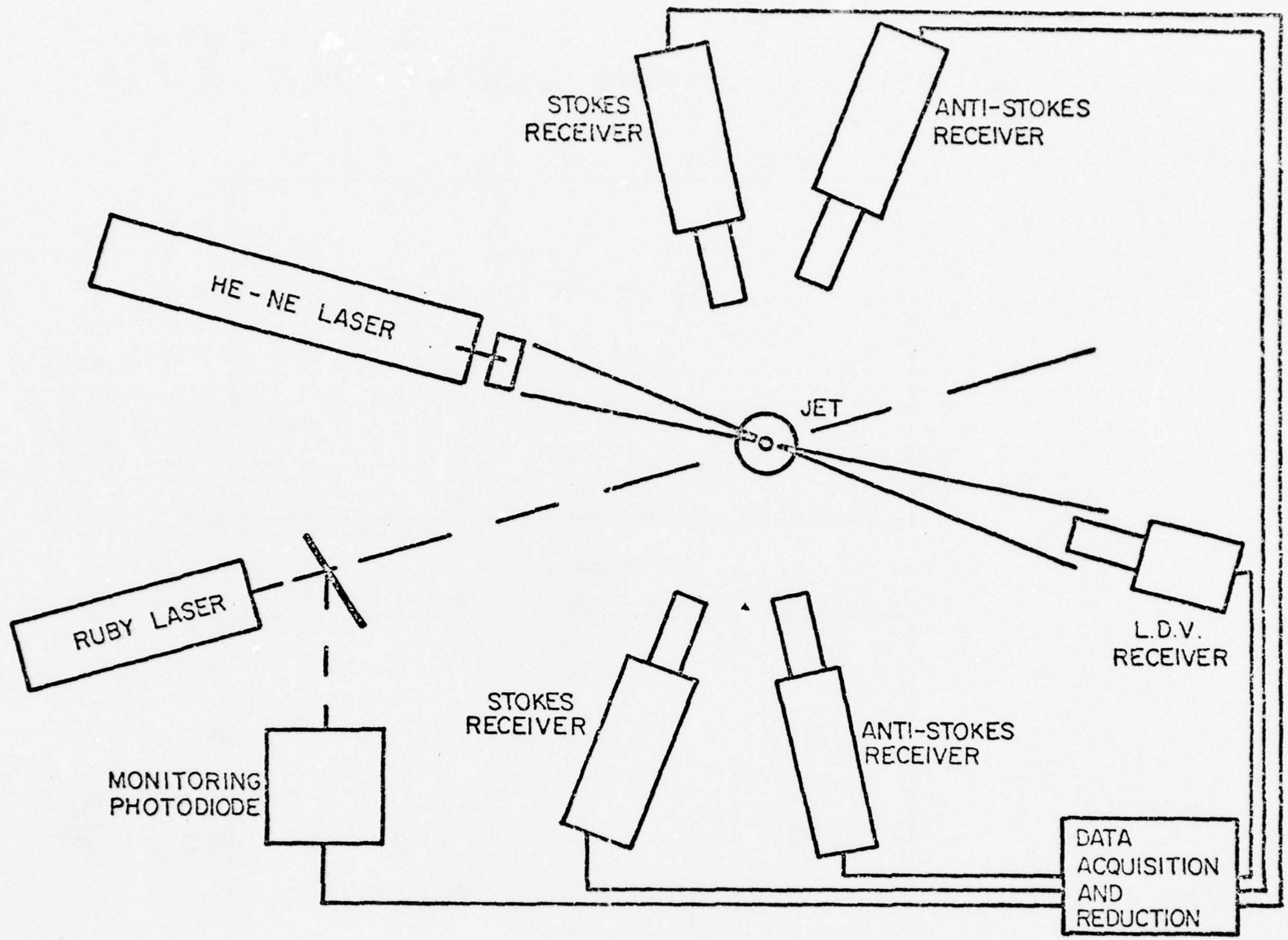
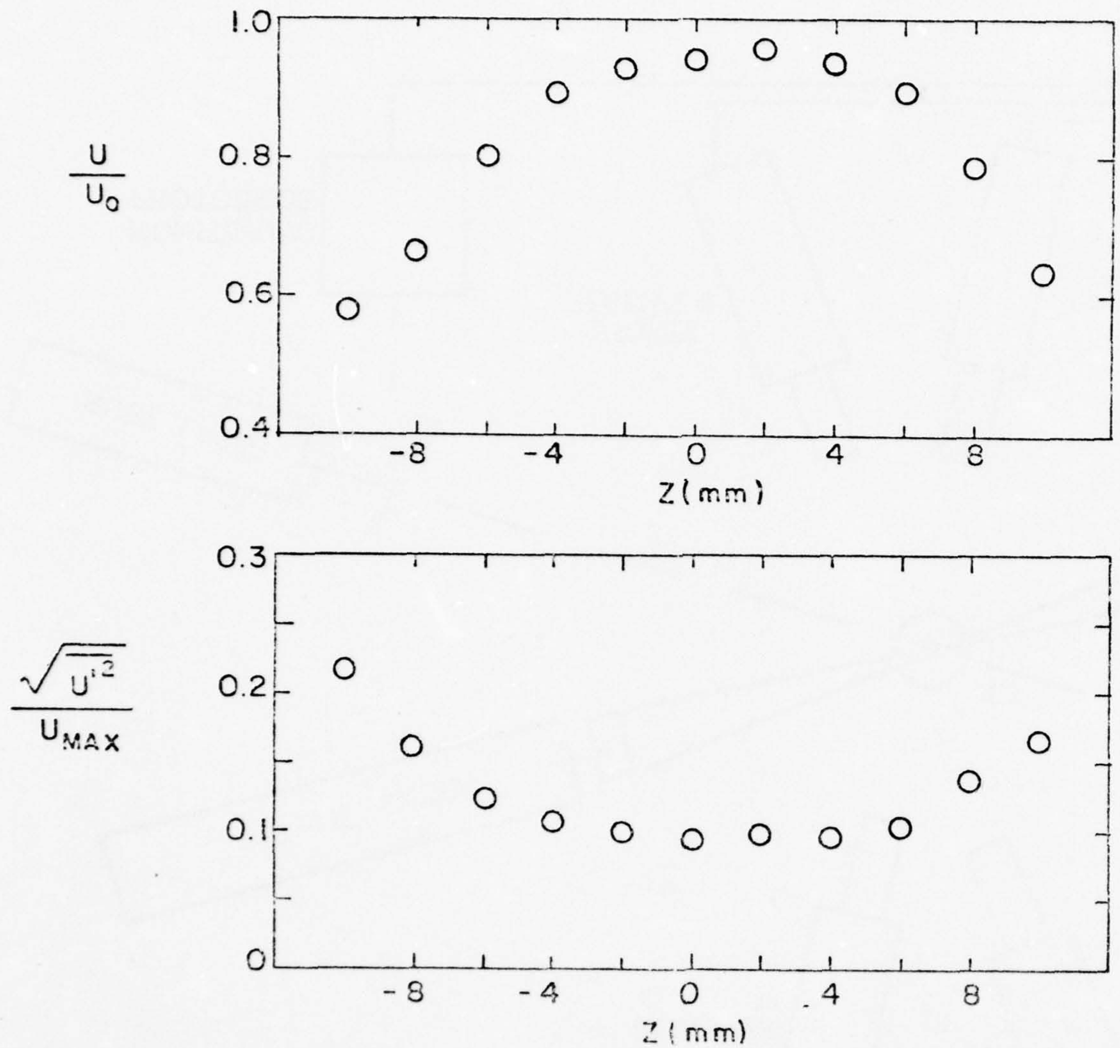
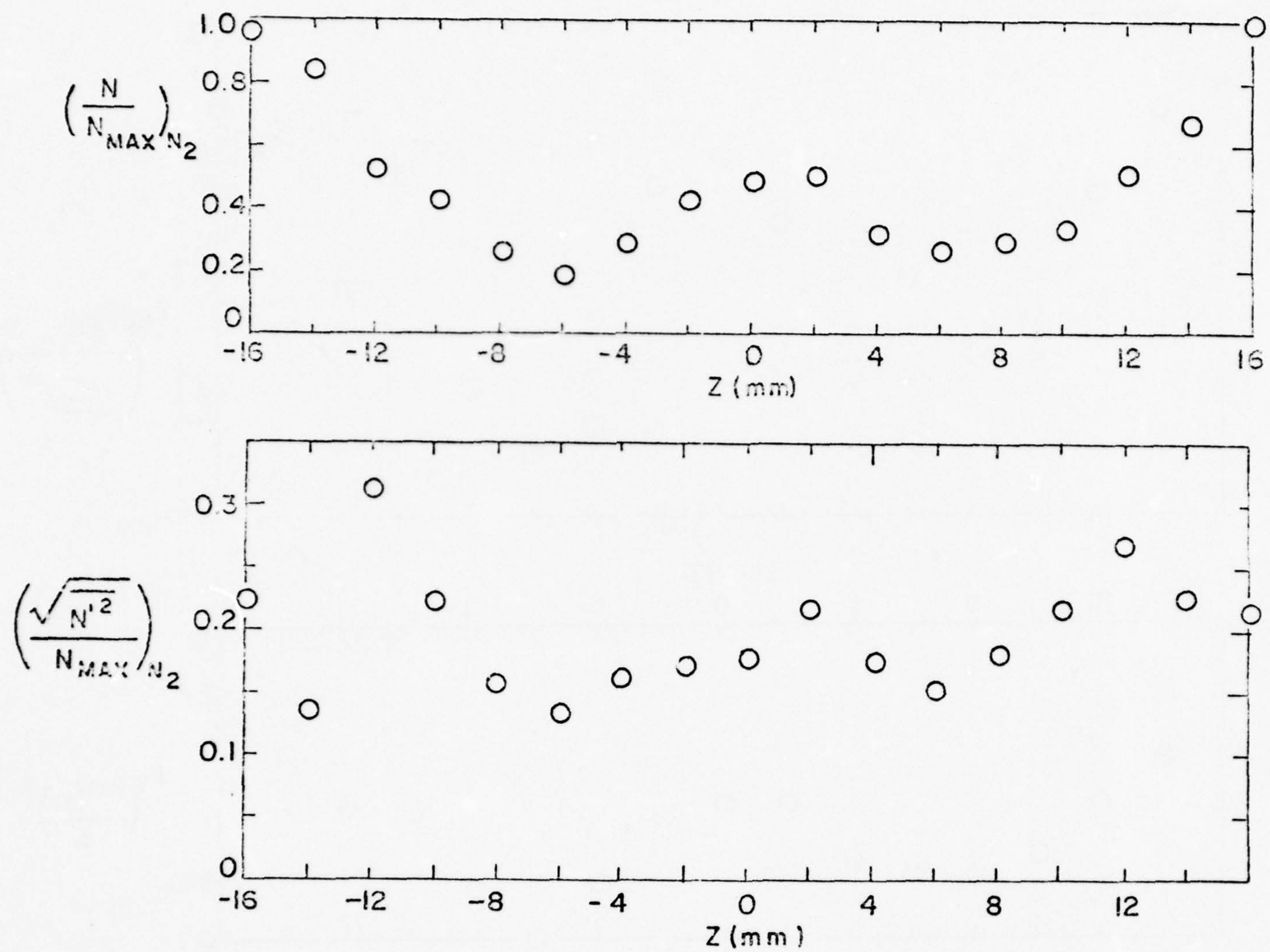


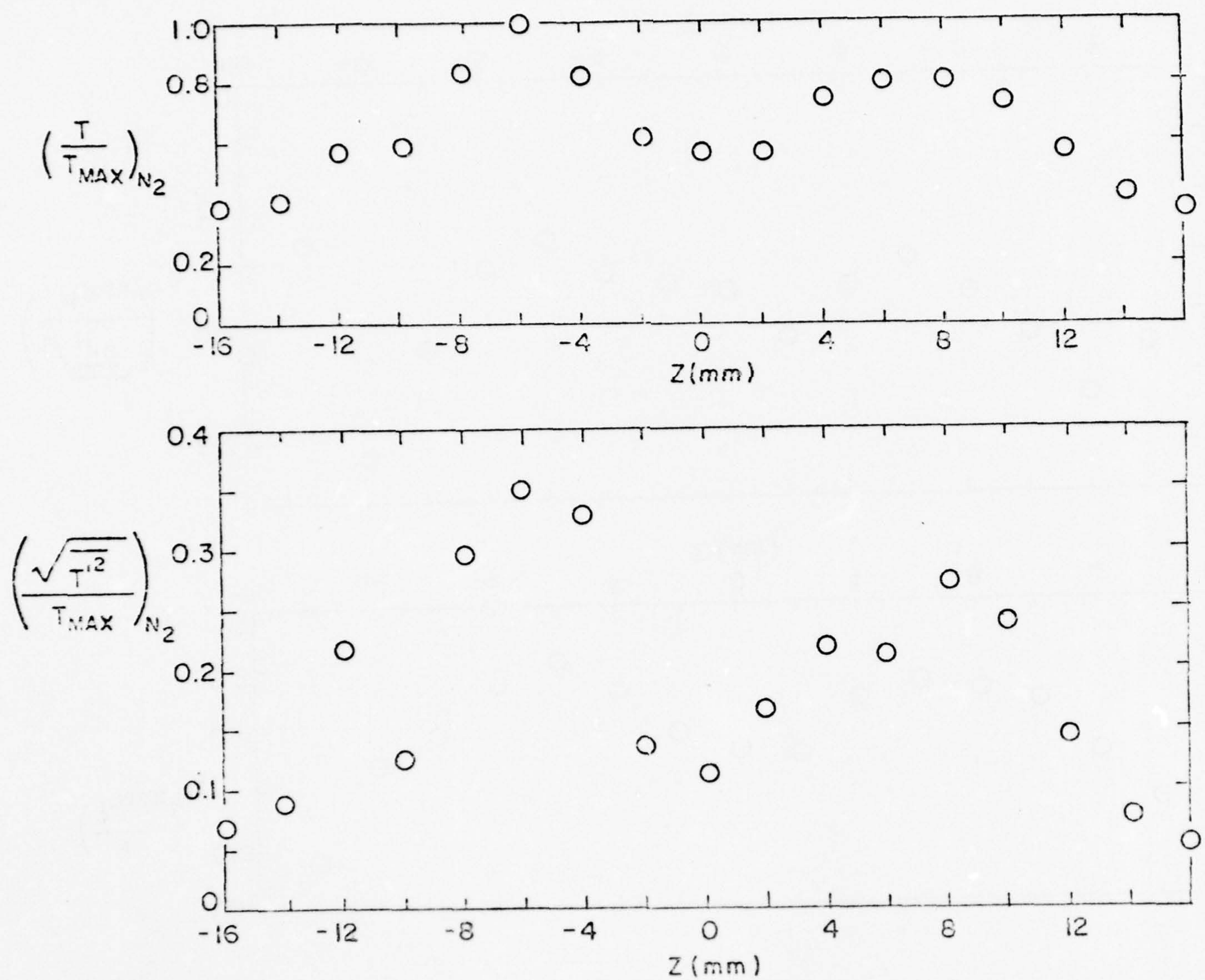
FIG. 1 BLOCK DIAGRAM OF EXPERIMENTAL APPARATUS



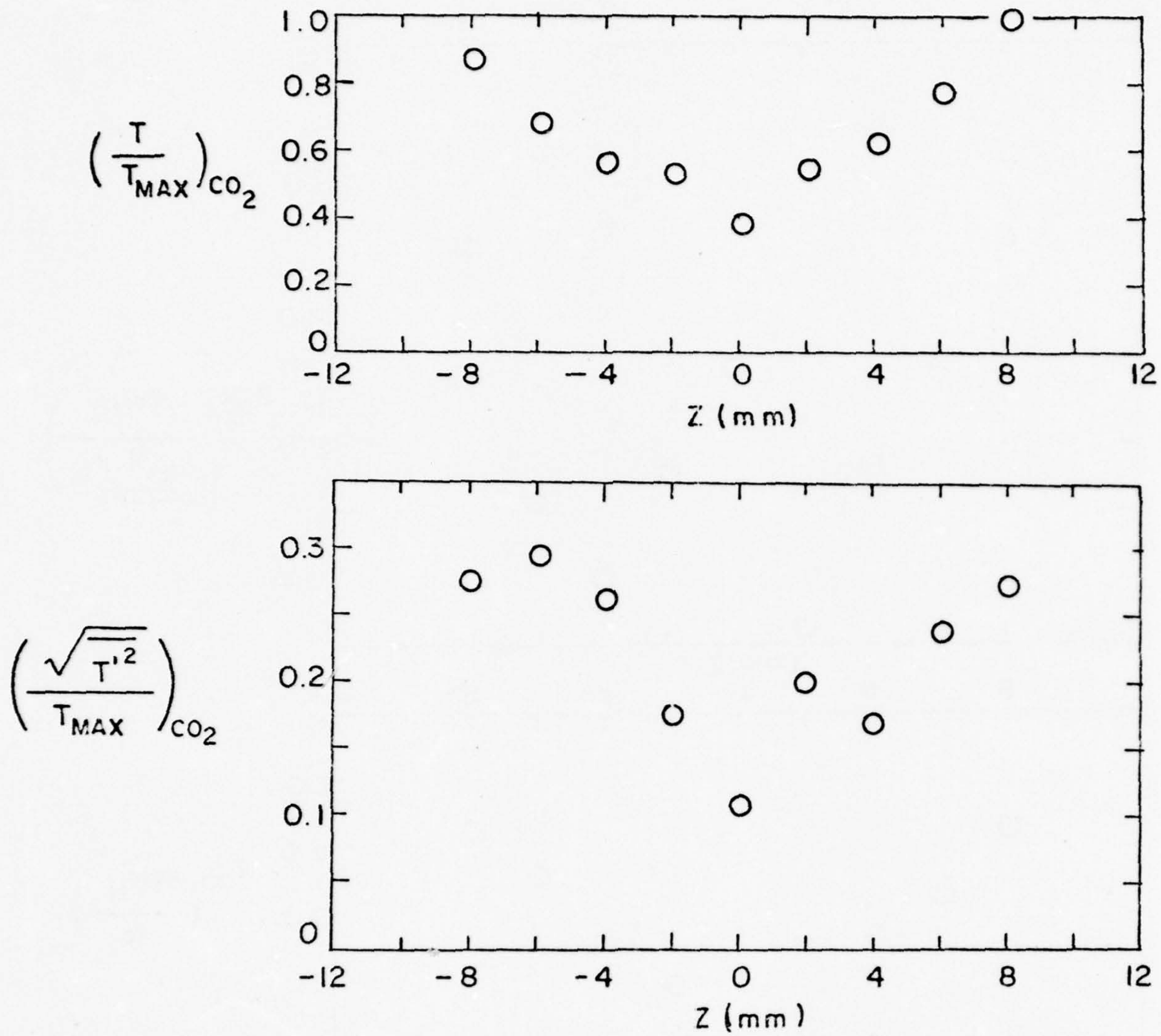
FLAME RADIAL VELOCITY PROFILE AT X/D = 7.143, U_0 = 44.99 FT/SEC



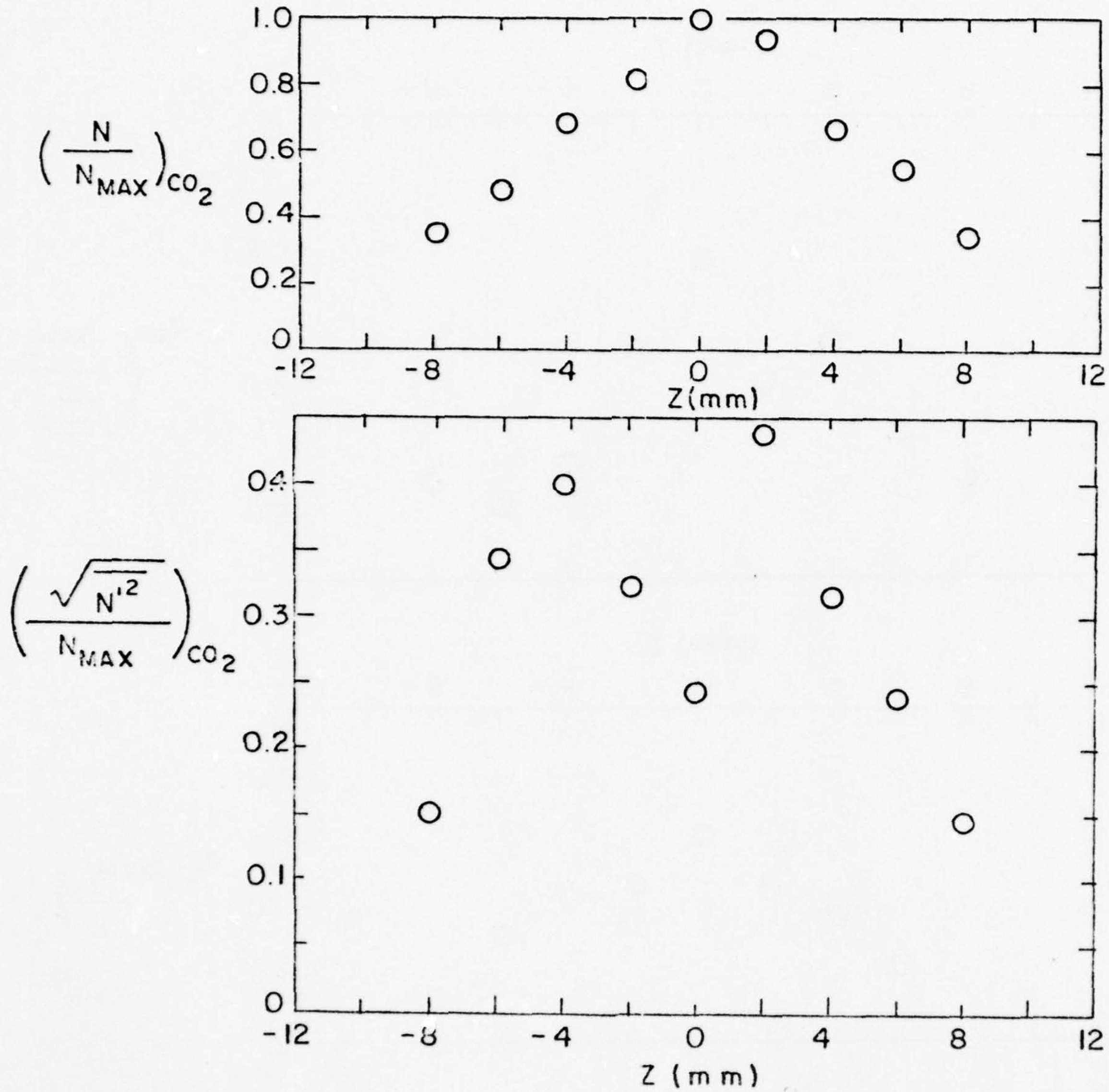
N_2 CONCENTRATION FLAME PROFILE AT X/D = 7.143



N_2 TEMPERATURE FLAME PROFILE AT X/D = 7.143



CO_2 TEMPERATURE FLAME PROFILE AT X/D = 7.143



CO_2 CONCENTRATION FLAME PROFILE AT X/D = 7.143

Semi-Annual Progress Report

LASER RAMAN PROBE FOR COMBUSTION DIAGNOSTICS

General Electric Company, Corporate Research and Development
Schenectady, N. Y.
Subcontract No. 8960-17

Marshall Lapp, Principal Investigator
Bruce W. Gerhold, Engineer
C. M. Penney, Physicist

Introduction

The coaxial jet burner combustion apparatus developed for the study of turbulence from laser velocimeter (LV) velocity data has been adapted and reassembled in order to apply vibrational Raman scattering (VRS) diagnostics. Radial profiles of the instantaneous value of temperature will be obtained at several downstream stations from the fuel tube, and comparisons made with the velocity turbulence data found during the previous Project SQUID contract period. We have solved many of the experimental VRS problems during this first half of the contract year; most specifically, the dye laser has been successfully line-narrowed and stabilized. Preliminary temperature surveys have been taken with thermocouples, in order to obtain some rough estimates of mean temperature for purposes of comparison.

Discussion

During this contract year, our objective is to obtain turbulent temperature data for a turbulent diffusion flame produced on a coaxial jet burner. This flame has been characterized by detailed turbulent velocity data from LV studies carried out during the previous contract year. The burner consists of a 2.7 mm-diameter hydrogen fuel jet axially centered in a 100 mm-diameter air duct, with care taken to remove any skewness from the flow. The LV characterization was produced over small volumes, of a size roughly given by a 0.5 mm length and 0.3 mm diameter. Both mean and turbulent velocities were obtained, and the resultant data indicated that direct coupling from the combustion process -- e.g., small-scale eddy dilation, heat release, etc. -- appear to be minimal effects in the production of turbulence. During the course of the present study of turbulent temperature profiles, we plan to obtain further information concerning the effect of combustion on the turbulence level in a co-flowing jet.

As a preliminary effort in this temperature study, thermocouple data have been taken which give rough estimates of radial temperature profiles at several downstream stations. These mean data show both resemblenses and differences with respect to the LV velocity data; they will serve to guide us in a general sense, but the VRS temperature data are likely to be different, because of their sub-microsecond time response.

The major effort during the first half of this contract period

has been spent on developing the dye laser source and the optical detection apparatus. We will describe here our results on the laser source, since this work has been key in the development of a practical diagnostic scheme. A Phase-R 2100 B coaxial dye laser is being utilized for the combustion scattering experiments. This laser is an advantageous source because it can provide 3 J pulses of good beam quality at several pulses per minute in the red and blue with tunability over approximately 30 nm within each of these wavelength ranges. Other types of lasers with similarly desirable capabilities are several times more expensive.

However, we, as well as other groups, have encountered several problems in adapting a dye laser for combustion experiments. These problems are related to spectral purity, line narrowing, stable tuning, beam quality, and dye lifetime. The first three of these problems have been solved by using three prisms of SF10 glass to refract light of the desired wavelength through 180°. These prisms are oriented near the position of minimum deviation within the laser cavity on the output mirror side of the dye cell. Tuning is accomplished by tilting one of the prisms. Since the incident angles remain within a few degrees of Brewster's angle, the configuration has very low loss, usually less than 2% per pass, and produces a strongly polarized output. The dispersion of SF10 glass is very large, and sensitivity to prism tilt is very small near the minimum deviation position. Consequently, we are able to get several joules output in a stable, narrow ($\lesssim$ 0.1 nm) line. The unwanted spectral intensity in the wings of the laser line is

reduced by a spatial filter following the output mirror, producing the high degree of spectral purity required for combustion measurements. We have found that the surface flatness of the prisms is quite important for this application -- the present linewidth of 0.1 nm is limited by the $\lambda/4$ flatness of the prisms we are using presently.

We have obtained a satisfactory beam quality of about ten times the diffraction limit by using a flat-flat cavity with approximately two meter mirror separation. Limited dye lifetime is a bothersome, but tolerable, remaining problem; our output energy degrades by about 50% after 100 shots for a one liter fill of 5×10^{-5} molar Rhodamine 6G dye solution in ethyl alcohol.

A spectrometer-television camera system has been developed to monitor the spectral distribution of the dye laser output on each shot. Three horizontal scan lines of the camera output frame immediately following the laser discharge are digitized and stored for persistent display on a monitor. This system revealed fluctuating multiple line outputs extending over 2-3 nm when two quartz prisms were used for line narrowing instead of the three in our final system. Additionally, when three SF10 glass prisms of poor surface flatness ($\sim 2\lambda$) were used, similar broad line outputs were revealed. We plan to utilize this spectrometer-television laser spectral line monitor in all of our VRS temperature studies, in order to convince us that 0.1 nm lines are produced for each shot, and in order to determine the corresponding line shapes sufficiently well for the resultant data reduction.

Notes and References

Recent publications and manuscripts related to this research effort supported by Project SQUID and by other parallel General Electric and government efforts are listed below:

1. J. C. F. Wang and B. W. Gerhold, "Measurements on Turbulent Hydrogen Flames in a Circular Air Duct," AIAA Paper No. 77-48 (1977).

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INVESTIGATION OF NOVEL LASER ANEMOMETER AND PARTICLE-SIZING INSTRUMENT

Stanford University, Stanford, California
Contract No. 8960-11

Adjunct Professor S. A. Self, Principal Investigator
Dr. D. J. Holve, Research Associate
Mr. C. Van Horn, Research Assistant

Introduction

The objective of this research is the investigation and development of a laser anemometer and particle-sizing instrument capable of making simultaneous, remote, in-situ measurements of velocity and particle size (2-50 μm) in two phase flows, with particular reference to liquid spray combustors. In addition, the instrument should be applicable to particulate laden flows in general, e.g. hot ash flows found in MHD exhaust or frozen ash flows found in the exhaust of a coal-fired power plant.

Particle Sizing

In the previous progress report we demonstrated our ability to calibrate the instrument for particles in the size range 2-50 μm and at

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the same time to adequately minimize background light.

The crucial problem for any in-situ particle sizing counter is to ensure that signals are only accepted from a uniformly illuminated control volume. Otherwise one cannot distinguish strongly illuminated small particles from weakly illuminated large particles. The control volume must be larger than the largest particle to be measured, but small enough that there is a low probability of there being more than one small particle in the volume at the same time.

The current set-up for achieving these objectives is shown in Fig. 1. Although the basic side scatter gating technique described previously (1) is being used, we have made several modifications described in the following paragraphs.

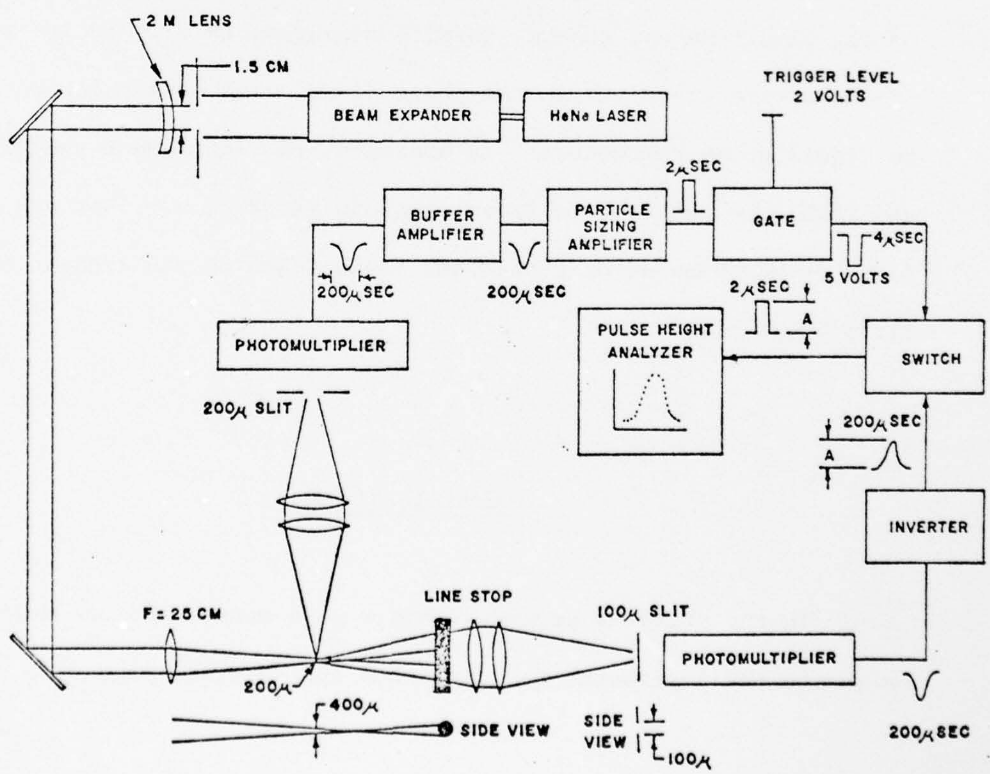

Fig. 1. Schematic of Particle Sizing Instrument.

The telescope with spatial filter expands the Gaussian-shaped laser beam to 5 cm diameter. The central portion of the expanded beam is apertured by a 1.5 cm diam. stop and focused by a long focal length cylindrical lens (f = 2 meters) in the horizontal plane. The long focal length is required for sufficient depth-of-field to give 400 μ beam width at the illumination volume and ≤ 1000 μ width at the horizontal line stop located about 20 cm from the illumination volume.

In the vertical plane another cylindrical lens (f = 25 cm) provides a uniform illumination profile in the horizontal plane about 200 μm wide and with ~ 30 μm wide edges. These edges will contribute about 25% error in the number-amplitude count but can be corrected for.

The width of the illumination volume along the illumination axis is determined by the vertical side-scatter slit which is set at 200 μm. The horizontal slit in the forward scatter mode is set at 100-200 μm which along with the other volume dimensions gives an illumination volume size of about 200 μm^3. This illumination volume size is adequate to handle a number density $\leq 10^5/cm^3$. Such a capability is adequate to handle a wide range of spray conditions except for regions of high density near a spray nozzle exit.

The flow direction of the test particles is perpendicular into the plane of Fig. 1 and must be maintained high enough to give ≤ 200 μsec risetime of the light scattering pulse seen by the side-scatter photomultiplier. For a 200 μm thick illumination path this implies a minimum velocity of 0.6 meters/sec. As a flow test vehicle we have used a channel flow with alcohol circulated by a peristaltic pump with

an ultrasonic bath as a reservoir so that we can add polystyrene spheres of known size.

When a particle passes through the appropriate illumination volume, the side scatter photomultiplier gives a negative output pulse which drives a particle-sizing amplifier. The particle-sizing amplifier senses the peak amplitude (corresponding to a particle passing through the peak intensity of the illumination volume) and gives a corresponding amplitude pulse of 2 μsec duration. This pulse in turn drives a gate generator for input pulses of 2 volts and greater. The side scatter photomultiplier gain is set so that the minimum particle size of interest just triggers the gate. When the gate is triggered, a standard 5 volt, 4 μsec pulse opens the analog switch which turns on the output of the forward scatter photomultiplier giving a 2 μsec pulse with amplitude corresponding to the peak amplitude in the forward scatter direction. Each pulse is then counted by the pulse height analyzer, placing each into the appropriate amplitude bin.

Fig. 2 shows the results for a nominally monodisperse distribution of 32 μm (± 10% RSD) polystyrene spheres at a concentration of $1200/cm^3$ (mass loading = 40 gm/m^3) in an alcohol solution. The size distribution displayed by the pulse height analyzer follows very closely that of the actual particle distribution except for some deviation at lower amplitude bins, which one would expect because of the 30 μm edge-width of the illumination volume. The results of Fig. 2 thus demonstrate proof of principle of the method.

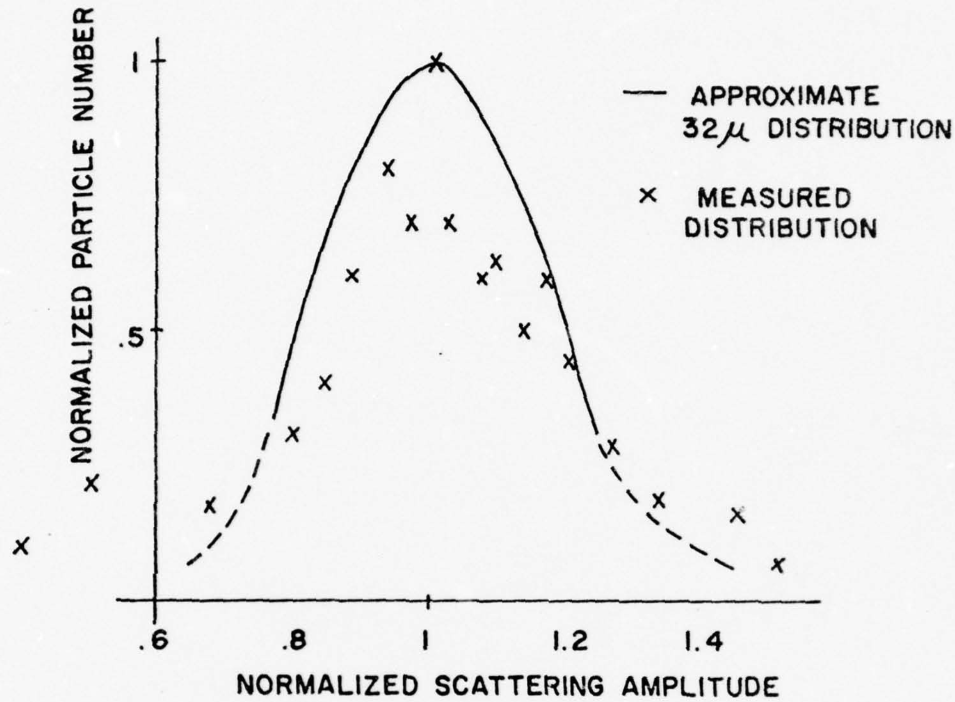

Fig. 2. Comparison of measured and actual size distribution for nominal 32 μm polystyrene spheres.

Remaining steps to be performed in perfecting the instrument are primarily of an electronics nature. The current analog switch is somewhat noisy, limiting the useable dynamic range. An improved switch is being acquired. Tests will then be performed with a mixture of monodisperse particles covering the 2-50 μm range using the present particle flow system and a recently acquired monodisperse particle generator. Quantitative measurements will be made to determine the appropriate electronics adjustments necessary for quantitative number density measurements. The final characteristic to be determined is the maximum allowable number density in the flow before multiple scattering events occur.

Reference (1) S.A.Self, "Investigation of Novel Laser Anemometer and Particle Sizing Instrument," Project SQUID Annual Report, 30 Sept. 1976.

IV. TURBULENCE

THE COHERENT FLAME MODEL FOR TURBULENT CHEMICAL REACTIONS

TRW Defense and Space Systems Group, Redondo Beach, California
Subcontract No. 8960-18

Dr. James E. Broadwell, Principal Investigator
Prof. Frank E. Marble, Consultant

Introduction

One of the most ambitious aims of aerothermochemistry is the rational analysis of turbulent chemical reactions. The problem arises in almost all technological combustion units and turbulent combustion processes are nearly universal in propulsion systems. In gas turbines, the performance and stability of both primary and secondary burners are concerned with turbulent combustion. Air-augmented rockets, or ram rockets, rely upon turbulent mixing and combustion for their entire performance. Current interest in pollutant formation by aircraft gas turbines has accentuated the importance of more details of the combustion process than were formerly required for practical problems. In the slow production of nitric oxide, the temperature history of the reacting element is an item of key importance. In a wider field, atmospheric chemistry and some phases of water chemistry are controlled by a turbulent mixing mechanism; the entire understanding of chemical lasers rests upon the details of the mixing and reaction process.

It is the objective of this project to develop a model for chemical reactions in turbulent flow. In particular, the aim is to analyze the case in which the chemical reaction rates are fast relative to the mixing processes.

Discussion

A description of the turbulent diffusion flame is proposed in which the flame structure is composed of a distribution of laminar diffusion flame elements, whose thickness is small in comparison with

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the large eddies. These elements retain their identity during the flame development; they are strained in their own plane by the gas motion, a process that not only extends their surface area, but also establishes the rate at which a flame element consumes the reactants. Where this flame stretching process has produced a high flame surface density, the flame area per unit volume, adjacent flame elements may consume the intervening reactant, thereby annihilating both flame segments. This is the flame shortening mechanism which, in balance with the flame stretching process, establishes the local level of the flame density. The consumption rate of reactant is then given simply by the product of the local flame density and the reactant consumption rate per unit area of flame surface. The proposed description permits a rather complete separation of the turbulent flow structure, on one hand, and the flame structure, on the other, and in this manner permits the treatment of reactions with complex chemistry with a minimum of added labor. The structure of the strained laminar diffusion flame may be determined by analysis, numerical computation, and by experiment without significant change to the model.

The flame density and the mass fractions of reactant are described by non-linear diffusion equations in which those equations for the reactants each contain a consumption or production term associated with flame surface stretching and a consumption term describing the flame shortening by mutual annihilation. Each of the equations contains a turbulent diffusion term utilizing a scalar diffusivity. The model of inhomogeneous turbulence, proposed by Saffman, completes the description of the problem and couples with the flame and composition equations to determine the velocity distribution and the turbulent diffusivity. A single additional universal constant, over those appearing in Saffman's model, is required in the model equations for the flame.

The coherent flame model has been applied to diffusion flame structure in the mixing region between two streams and predicts correctly the result that the reactant consumption per unit length of flame is independent of the distance from the initiation of mixing. In this example which is carried out for small density changes, both the fluid mechanical and flame variables possess similarity solutions.

The coherent flame model is also applied to the turbulent fuel jet which clearly does not have a similarity solution simply because the finite mass flow of fuel is eventually consumed. The problem is solved utilizing an integral technique and numerical integration of the resulting differential equations. The model predicts the flame length and superficial comparison with experiments suggest a value for the single universal constant. The theory correctly predicts the change of flame length with changes in stoichiometric ratio for the chemical reaction.

An account of the work is contained in Project Squid Technical Report TRW-9-PU, entitled, "The Coherent Flame Model for Turbulent Chemical Reactions," by Frank E. Marble and James E. Broadwell, dated January 1977.

LARGE SCALE STRUCTURE AND ENTRAINMENT
THE TURBULENT MIXING LAYER

University of Southern California, Los Angeles, California
Subcontract No. 8960-12

Associate Professor F. K. Browand, Principal Investigator
Mr. B. O. Latigo, Research Assistant

Introduction

The purpose of the present experimental studies is to gain a better understanding of the dynamics of the turbulent mixing layer. Attention is focused on the largest features in the mixing layer -- the quasi-organized vortical structures which are aligned across the flow in a roughly two-dimensional fashion. The characteristic interactions of these vortical structures are presumed to be the controlling element responsible for mixing layer growth, and to provide the setting within which the smaller scale mixing takes place.

Discussion

Our measurements of last year show that the lateral distributions of mean velocity and RMS longitudinal fluctuation, when plotted against a normalized coordinate, become independent of downstream distance and become independent of the character of the boundary layer at the point of shear layer initiation. For either laminar or turbulent initial conditions, the growth rates of the local (lateral) length scale approach each other also. This suggests that a universal similarity may exist, although it may be difficult to achieve in practice. The consequences of a possible universal similarity form (for all measureable time averaged properties) can be examined in terms of four unknown quantities. There are:

1) the growth rate of the lateral length scale, $d\theta/dx$;

2) the position of the mixing region, dy_0/dx;

3,4) the mean lateral velocities at the two sides of the mixing layer $v(\pm\infty)$.

In the four describing equations (continuity, mean momentum, moment of momentum and turbulent kinetic energy) only one inhomogeneous term is present -- the total turbulent dissipation. The solution, in general, requires non-zero values for the mean lateral velocity at both edges of

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the mixing layer; we are presently using experimental data to obtain a solution.

The large instantaneous values of u'v' which occur intermittantly in the outer regions of the mixing layer contribute the overwhelming proportion of the (time averaged) Reynolds stress. For example, at a lateral position corresponding to the outer edge on the high speed side, 75% of the Reynolds stress, $\overline{u'v'}$, domes from events which exceed the mean value by a factor of more than 35, and which occupy only 15 percent of the total time record.

Computer programs have been written to determine the distribution of time intervals associated with these large amplitude events. The probability distributions of time intervals show important contributions for intervals up to about 10 times the mean vortex passage period (as determined from autocorrelation measurements) but beyond this, there is very little contribution.

Interactions of the large scale vortices are studies by a conditioned sample technique using the signals from two detector probes to form the instantaneous sample criterion. The intermittant occurrences of large perturbation momentum flux, u'v', are definitely correlated with the passage of the large scale vortical structures. Conditionally sampled results at many lateral positions across the shear layer, give an approximate spatial picture consisting of a large vortical structure on the high speed side preceding a second large vortical structure on the low speed side. Present efforts are to extend the procedure to obtain a sequence of instantaneous "snap shots" of the mixing layer.

BINARY GAS MIXING WITH LARGE DENSITY DIFFERENCE IN HOMOGENEOUS TURBULENCE

Studies of the Basic Phenomena Associated with Molecular Diffusivity Effects in Turbulent Mixing

Michigan State University, East Lansing, Michigan

Subcontract No. 4964-49

Professor J. F. Foss, Principal Investigator
Mr. K. C. Cornelius, Graduate Research Assistant

INTRODUCTION

It is the purpose of our research to illuminate, and to provide quantitative measures of, the fundamental phenomena which are responsible for the strongly enhanced molecular diffusivity effects in a turbulent mixing field. The presence of these effects is of obvious importance in the combustion process; their full exploitation requires an understanding of their dependence upon the character of the turbulence field. One approach toward this understanding is to examine the results of controlled variations in the governing parameters of experiments which are (1) sufficiently simple that the cause/effect relationships are least ambiguous and (2) sufficiently similar to the technological problem that the phenomena of interest are preserved. Our experiments examine the mixing of two distinct rectangular volumes by light scattering measurements from the central region of a closed mixing chamber. The nature of the experimental facility allows the initial turbulence structure in the two volumes to be individually controlled and stable, unstable or neutral density mixing may be investigated.

Each scan of the mixing region can be executed in ($\geq$) 3.1 msec and the collection optics can be adjusted to examine a scan length (ℓ) of $7.3 \leq \ell \leq 17$ cm. The minimum scattering volume length is defined by the width of the helical slit divided by the cosine of the intersection angle (22-45 degrees) with the vertical scattering line. The nominal net dimension, for the experiments completed to date, has been ≈ 0.35 mm. The nominal diameter of the focused laser beam, over the 74 mm scan length, was 0.25 mm. These lengths define the observed scattering volume for the present experiments; data were taken from 205 scattering volumes per scan. The ultimate experimental capability will allow measurements of the non-diffusive mixing of the two volumes, species concentration (Rayleigh scattering) measurements and velocity (L.D.V.) measurements. The present experiments have been executed with a non-diffusive contaminant marking the lower half-volume. (Non-diffusive: nominal 0.7 μ particulate matter for which the Brownian motion diffusivity

is small....D $\approx 10^{-14}$ cm^2/sec and $\delta = (Dt)^{1/2} \approx 3\times10^{-3}$ mm in the 0.2 sec elapsed time of interest...and for which the particulate response time to the continuum motion is rapid... $\tau \simeq 10^{-7}$ sec.) The marked/unmarked spatial volumes following the passage of the grid/splitter plate are associated with the convective transport of the turbulent mixing field.

DISCUSSION

The experimental results from two ensembles of experiments have been processed and interpreted. These results are of intrinsic interest and they are the basis for several major decisions regarding the future course of this research. These matters will be briefly identified herein. The complete explication of the former will appear in the technical report and the January 6, 1977 proposal to Project SQUID identifies the latter.

The two ensembles of experiments formed from 69 realizations of air/air and 100 realizations of Freon 12/Freon 12 in which the lower chamber was marked with the non-diffusive contaminant. The plate/grid speed of 6.28 mps and the mesh size of 25.4 mm were common to all of the experiments. The kinematic viscosity of air is 5.8 times greater than Freon 12; the respective Reynolds numbers (UM/ν) were 10^4 and 6×10^4.

Ensemble mean values of the concentration were satisfactorily fit to a standard Gaussian distribution, $A(\zeta)$, via the expressions:

$$A(\zeta) = \int_{-\infty}^{\zeta} \exp\,(-\alpha^2/2)\, d\alpha$$

$$\zeta = my + B; \qquad A(\zeta) = \langle\Gamma(\zeta)\rangle$$

in which m^{-1} serves as a width measure of the $\langle\Gamma(y)\rangle$ field. Strikingly, m^{-1} for the Freon experiments was significantly less than m^{-1} for the air at a given elapsed time. It was concluded that the smallest scales of the Freon provide non-diffusive striations of the marked fluid which are small with respect to the scattering volume dimensions; the binary

comparator circuit is not able to distinguish the relative state of contamination and hence considers marked fluid to occupy the volume. The design of a finer slit--100 μ width--has been achieved using the CALCOMP plotter to form the curve at four times real scale and a photographic reduction to produce the master for an etched metal cover plate. The plate will be attached to the present disc. Additional support will be required to fabricate this item.

The individual measurements of Γ in the "instantaneous" scans of the turbulent mixing field represent a very considerable amount of information which is only partially characterized by the $\langle\Gamma(y,t)\rangle$ distributions. Insight into the detailed structure and processes of the mixing field can be gained if suitable measures of the instantaneous scans can be formulated. One such formulation has been achieved; it is described below.

Consider two extreme cases for the instantaneous concentration field; both are capable of yielding the observed $\langle\Gamma(y,t)\rangle$ following the ensemble average process. The two cases are introduced in the form of statements. The instantaneous concentration field is such that an instantaneous scan reveals:

1. a well mixed field with transverse dimension and concentration $\Gamma(y,t)$ "similar" to that of $\langle\Gamma(y,t)\rangle$.
2. a relatively thin mixed region (i.e., one which is small, for example, with respect to $m^{-1}(t)$) which is laterally transported by the convective action of the large scale turbulent motion to yield the observed $\langle\Gamma(y,t)\rangle$ distribution.

It is not expected that either of these models will be supported in their extreme condition; however, they do serve as a guide for the definition of measures to evaluate the character of the instantaneous scans. The definition of additional terms is necessary for this description; the quantities $\sigma_{\Delta y}$ and YS can be shown (Technical Report in preparation) to characterize the transport of the mixed region by the large scales of the turbulence field and the width of the instantaneous scans respectively. The results, presented

in Figure 1, are quite instructive. Specifically, it is seen that the mixed region is approximately 40% of the ensemble mean width and that the turbulent transport is the principal effect which accounts for the ensemble width of the mixing region. It is also seen that the turbulence field is quite quickly established.

The present experimental results can also be interpreted in the context of the central motivation for these studies: to provide experimental results which clarify the role of molecular diffusivity effects in a turbulent mixing field. The instructive character of the results is directly related to the "simplicity" of the turbulence field; this was the original motivation for constructing an experiment in which the mixing would occur in the homogeneous field of grid turbulence. This motivation appears to be fundamentally thwarted by the nature of our experimental technique; namely, the influence of the mixing field from the splitter plate wake and the impulsively started boundary layers dominates the results within the initial time period. Since this initial time period controls the character of the mixing results and since the mixing field grows beyond the field of view for times which can be safely identified as having achieved the homogeneous state, it is suggested that a different "basic state" of the turbulence field be considered for future experiments. A basic state which is readily achieved and which, when adequately documented, will serve the purpose of the research, is that provided by the wake of the receeding plate and the interaction of the initial, impulsively started, boundary layers. Significantly, this basic state is more closely related to the combustor flows which serve as the technological motivation for these studies. It is also a basic state for which controlled alterations of the principal parameters can be readily achieved. A fine mesh screen can be placed upstream of the trailing edge to create a background turbulence field for the wake-boundary layer mixing region. The relative dimensions of the wake and boundary layer thickness are subject to the independent controls

of plate speed and thickness. Unequal velocities of the gas past the splitter plate could be achieved by mounting a barrier on the frame which supports the splitter plate.

The final alteration of the experimental program, which is inferred to be desirable as a result of this initial experience, is the acquisition of the amplitude of the scattered radiation for the non-diffusive mixing experiments. This will be possible since our concurrent work to develop a species measuring capability has resulted in the appropriate electronics to create a 10-bit representation of the photomultiplier tube output for each 4 μsec of the scan. Several options exist for the configuration of the experiments but it appears that the available core memory of the minicomputer will be sufficient to store the large data volume to be generated by this technique. The data processing will be less ambiguous than the current analog voltage discrimination; however, it will not be unambiguous since the level of the scattered radiation is not uniform from the marked fluid. That is, the relatively small number of particles per scattering volume creates a natural (statistical) variation in the signal strength. Appropriate analysis of the signal levels will be required; the basis for this analysis can be taken from the scattering characteristics at the initiation of the mixing and at a long elapsed time when the striations are pervasive.

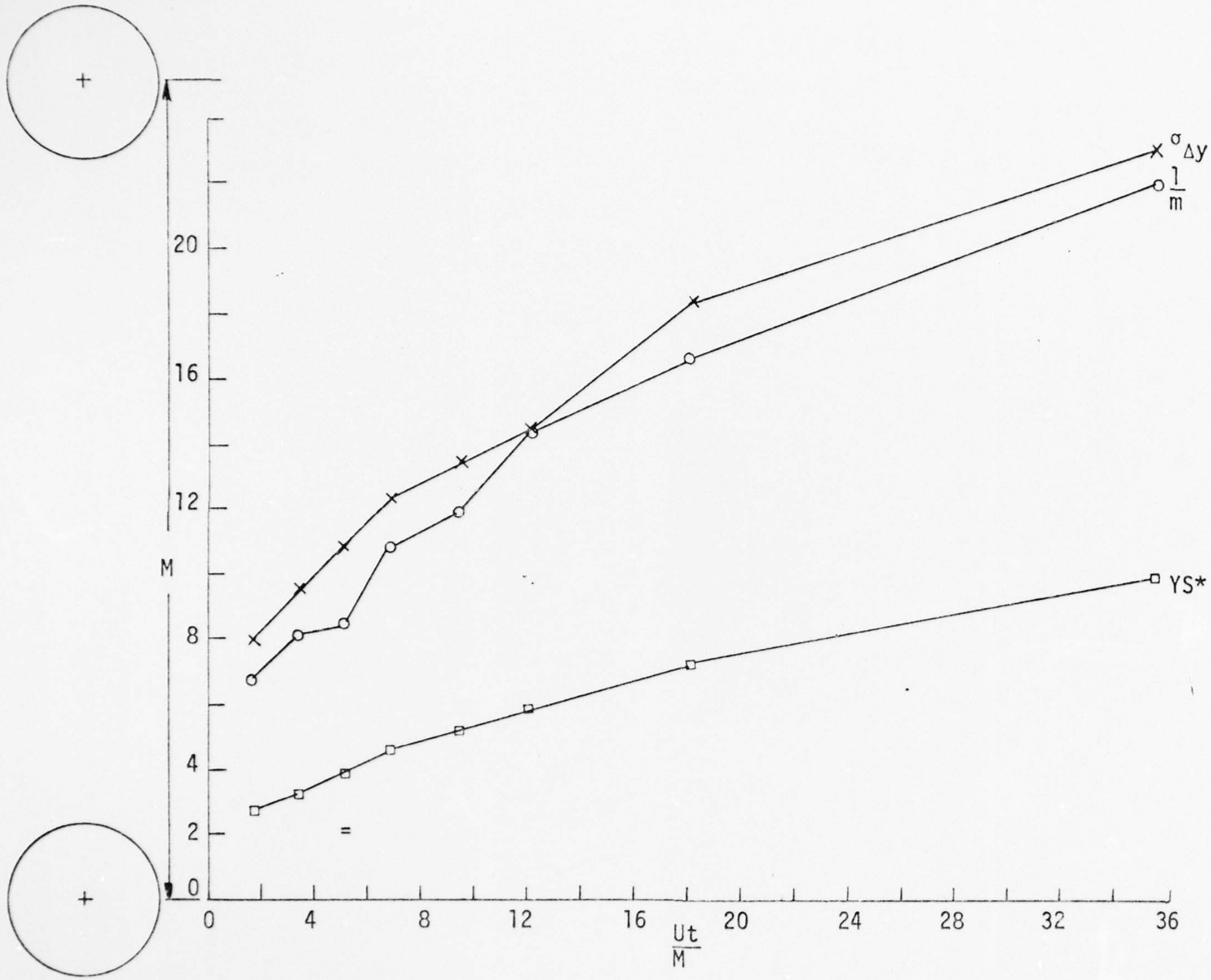

Figure 1. Measures of the mixing region width as determined from the instantaneous scans

Notes: Rod and mesh sizes of the biplane grid are shown for reference.

HETEROGENEOUS TURBULENT FLOWS RELATED TO PROPULSIVE DEVICES

University of California, San Diego
Subcontract No. 4965-26

Paul A. Libby
Principal Investigator

Introduction

This research addresses problems related to the turbulent heterogeneous flows which arise in a variety of propulsive devices when reactants and products mix and react. The effort is both experimental and theoretical; the experimental program concerns exploitation and extension of the multiple sensor "hot wire" technique of Way and Libby which permits time-resolved and space-resolved measurements of velocity and concentration of one light species, e.g., helium, in a mixture of light and heavy gases under isothermal conditions. The application of this technique in the present research is to a confined internal flow corresponding to an idealized combustor. The related theoretical work supports the experimental effort and attempts to extend the results thereof to flow situations of more practical concern, e.g., to chemically reacting flows.

Discussion

During the past six months our theoretical effort has been concerned with a continuation of our studies in collaboration with Professor K. N. C. Bray of the University of Southampton on turbulent reacting flows with premixed reactants. In reference 1 we present the results of an application of the Bray-Moss model for premixed

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combustion to the oblique, planar turbulent flame. The principal result from this study is clarification of the effect of heat release on turbulent kinetic energy, namely that for nearly normal flames the dilatation of the flow due to heat release diminishes the turbulent kinetic energy whereas for highly oblique flames the shear stress which accompanies the heat release generates additional turbulence.

One aspect of our continuing follow-on effort to reference 1 concerns improvements to the theory to bring prediction and experiment in better agreement in those limited cases in which comparison with the original theory is possible and to extend the theory so as to widen the range of experiments amendable to such comparison. With respect to the first improvement we have completed a study (reference 2) in which the Prandtl-Kolmolgoroff model for the diffusion of turbulent kinetic energy and of the mean product concentration and the model for the scalar dissipation, models required for closure in the theory, are modified to account explicitly for variable density effects. The consequence of the modifications is that the original equations are altered by the inclusion of a density ratio to an arbitrary exponent m, which can be chosen to improve agreement between prediction and experiment.

Since such comparison is more direct, less subject to ambiguity, if carried out in terms of the so-called "strong interaction case" in which the turbulence generated by the flame overwhelms that in the on-coming stream, we have selected m on the basis of that case. In Figure 1 taken from reference 2 we show the original prediction of the flame angle θ, that denoted $m = 0$, and that of the revised theory with $m = 2$. For values of the heat release parameter τ in the range of practical interest, namely four to nine, the revised prediction represents an improvement in two respects. First, the predicted angles are considerably closer to experimental values, roughly twelve degrees versus three to six degrees found experimentally. Second the angle is relatively insensitive to τ, a result in agreement with experiment. Larger values of m could improve further the agreement with experiment but in our view pushing the comparison excessively appears unwarranted in view of the idealizations involved in the theory. In addition modest alterations of the empirical constants taken from constant density turbulence can rationally improve the agreement if desired.

The main point to be made from this study is that variable density effects should be taken into account in the modelling employed to achieve closure in analyses of turbulent flows involving variable density effects. How to include such effects is, of course, the subject of continuing research.

We should also mention another aspect of the results presented in reference 2; it also relates to variable density effects and concerns a comparison of conventional and Favre averaged statistics of quantities within turbulent premixed flames. Despite the appeal of Favre-averaging in terms of the phenomenology of turbulent flows with variable density, namely that the describing equations are considerably simplified, it has not been employed extensively presumeably because of concerns regarding the modelling to effect closure. The fact that the same concerns exist with conventional averaging appears to be mainly disregarded.

Given this situation, we consider it of interest to compare the distribution of various statistical quantities as given by conventional and Favre averaging in oblique, planar flames with premixed reactants. The Bray-Moss model and the Bray-Libby application thereof permit analytic comparisons of these quantities to be made. Briefly, we note that reference 2 shows that in such flames there are considerable differences in the distributions of the statistical quantities as given by the two means of averaging. Also noted in reference 2 is that the usual calculation based on conventional averaging with the correlations involving density fluctuations neglected, is inconsistent, corresponding to Favre-averaging in the convective terms and conventional averaging in others, for example, in the diffusive terms.

Presently underway is an effort directed at extending the theory so as to permit a wider range of experiments to be subject to comparison. We refer to consideration of large but finite values of the Reynolds and Damkohler numbers. The original calculation should be considered in this context to correspond to the first order terms in an expansion for inverse powers of these two numbers. We have now developed separate, second-order solutions in this expansion for the case of normal flames with highly dilute reactants and have completed the numerical analysis thereof. This is considered only the first step in this study and not to be of particular interest in itself. When completed we shall establish the first-order effects of finite Reynolds and Damkohler numbers.

Our experimental effort during the past six months has been concerned with completing the analysis of the data from our experiment on a two-dimensional jet of helium discharging into a moving airstream. This analysis is now complete and the results will be issued as a Project SQUID report in the near future. Here we present highlights of this study.

At the outset it is worth noting that the far-field of the two-dimensional jet should be identical to the far wake of a cylinder in appropriate similarity variables. The remarkable fact noted recently

by Rodi[3] is that there is no available data from a two-dimensional jet in a moving stream sufficiently far from the origin of the jet to correspond to the far field; our data does not fill this void but rather corresponds to an intermediate range of downstream distance. For purposes of data presentation we are able to identify a virtual origin but this is not the virtual origin for the far field and our results are not directly comparable to existing wake data.

A consequence of this situation is that our results and those of all previous investigators of the two-dimensional jet are of engineering rather than fundamental interest. It is noteworthy that data on helium as a passive scalar from our experiment but sufficiently far downstream to correspond to the far field would in fact differ from temperature in the heated wake in those respects influenced by molecularity. This difference would appear, for example, in the structure of the superlayer between turbulent and non-turbulent fluid and would be due to the difference between the Prandtl number for air and the Schmidt number for dilute helium-air mixtures. We shall indicate later that even in the middle region of the jet development, there are indications of this difference.

In Figures 2 and 3 we show the distributions in terms of a pseudo-similarity variable of the unconditioned streamwise velocity component and mass fraction of helium at various downstream stations. These results are in accord with expectations, and in agreement with previous results where comparison can be made. In Figure 4 we show the distribution of intermittency determined by discriminating between the turbulent and non-turbulent fluid on the basis of a level of helium concentration. There are no previous measurements of this quantity but again the results are more or less as expected from previous results on the wake of a cylinder.

In Figures 5 and 6 we show the result of combining the intermittency function with the time series in streamwise velocity and mass fraction of helium to obtain conditioned statistics, namely mean values within the turbulent fluid alone. Of particular interest is the value of 0.4 obtained for the helium concentration within the turbulent fluid as a fraction of the concentration on axis. This value agrees well with the corresponding asymptotic value for the temperature in the turbulent fluid of the heated wake.

We have also analyzed the data in terms of so-called range conditioned point statistics. This view of the results should be considered to involve the collection of all turbulent passages of a given time duration at a given station, the dissection of those durations into

equal time intervals, and the development of the statistics of the flow at those discrete time intervals. The result of this analysis is a picture of the statistical behaviour of turbulent structures of a given spatial dimension. The results in Figure 7 show the helium concentration for four different turbulent durations, all lined up at their upstream edges. The remarkable result is that the leading edges and the middle regions of the turbulent structures are essentially independent of the length of the burst. Similar results are obtained for the other statistics of the velocity and concentration. These results can be compared to recent results obtained by LaRue[4] in the turbulent wake of a heated cylinder. In the wake case the turbulent fluid moves slower than the external stream and therefore similarity of the turbulent structures requires that their downstream edges be lined up. Note that in the jet case the turbulent fluid moves faster than the external flow.

One interesting aspect of the wake and helium jet results in terms of range conditioned point statistics is the thickness of the leading and trailing edge regions, where molecularity is significant. We find in the helium jet that these regions are roughly fifty Kolmolognoff lengths thick whereas LaRue and Libby[5] found the corresponding thickness in the wake to be ten Kolmolognoff thicknesses. The difference in the two results is attributed to the considerably larger Schmidt number of helium in dilute helium-air mixtures compared to the Prandtl number of air.

At the present time we are setting up an experiment to extend further these results for the two-dimensional helium jet and to conduct a new experiment involving heated helium discharging into a moving stream. The latter experiment is of interest since it involves two passive scalars with different molecularity. The structures of the superlayer in this case will be of interest. In addition work on the modification of our low-speed wind tunnel to allow adjustment of the streamwise pressure gradient is going ahead.

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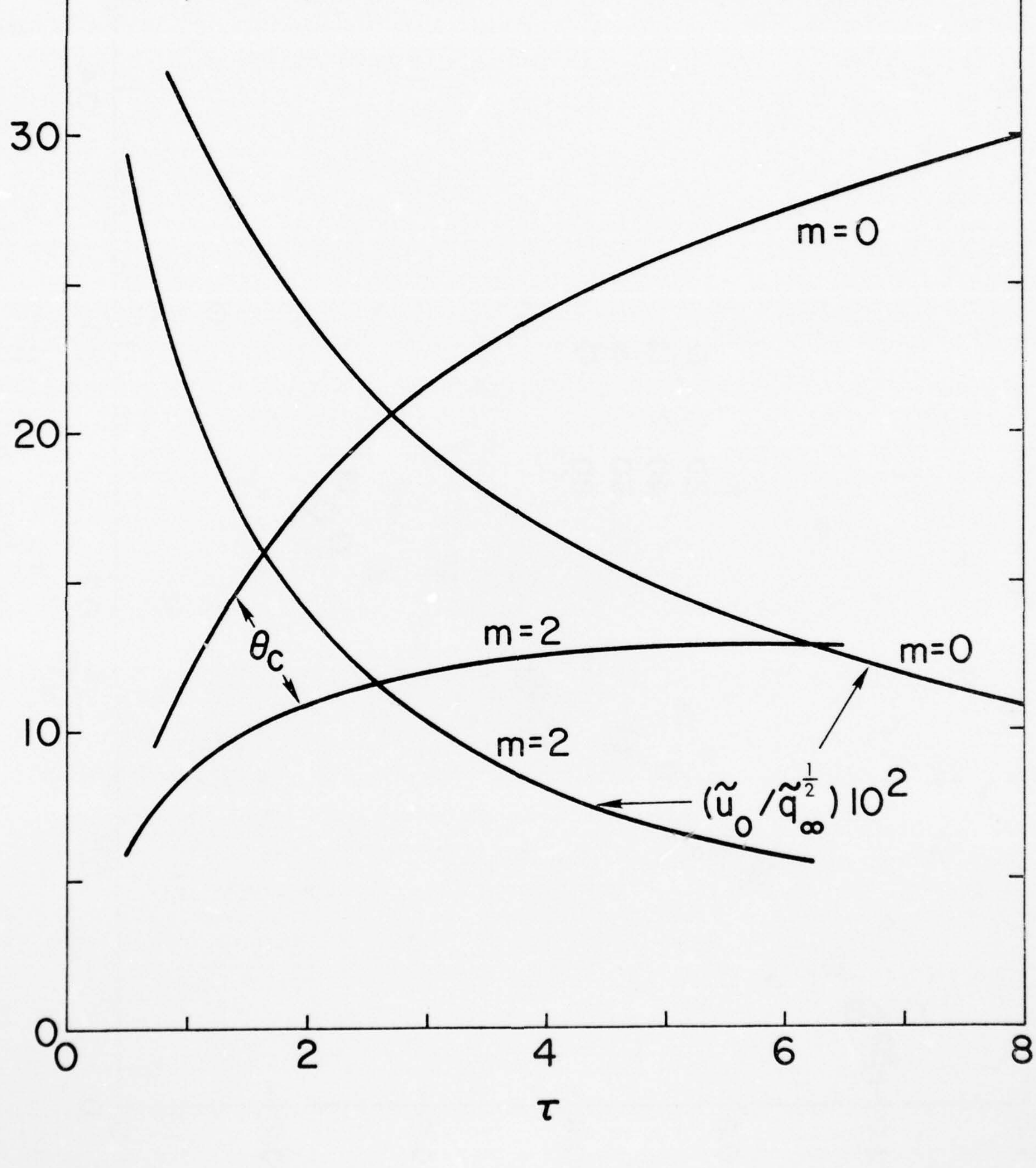
List of Figures

6. Variation of the mean mass fraction of helium within the turbulent fluid in a two-dimensional helium jet in a moving airstream in terms of similarity variables.

7. Range conditioned point statistics for the mass fraction of helium in turbulent bursts of various durations. All burst alined at their downstream edges.



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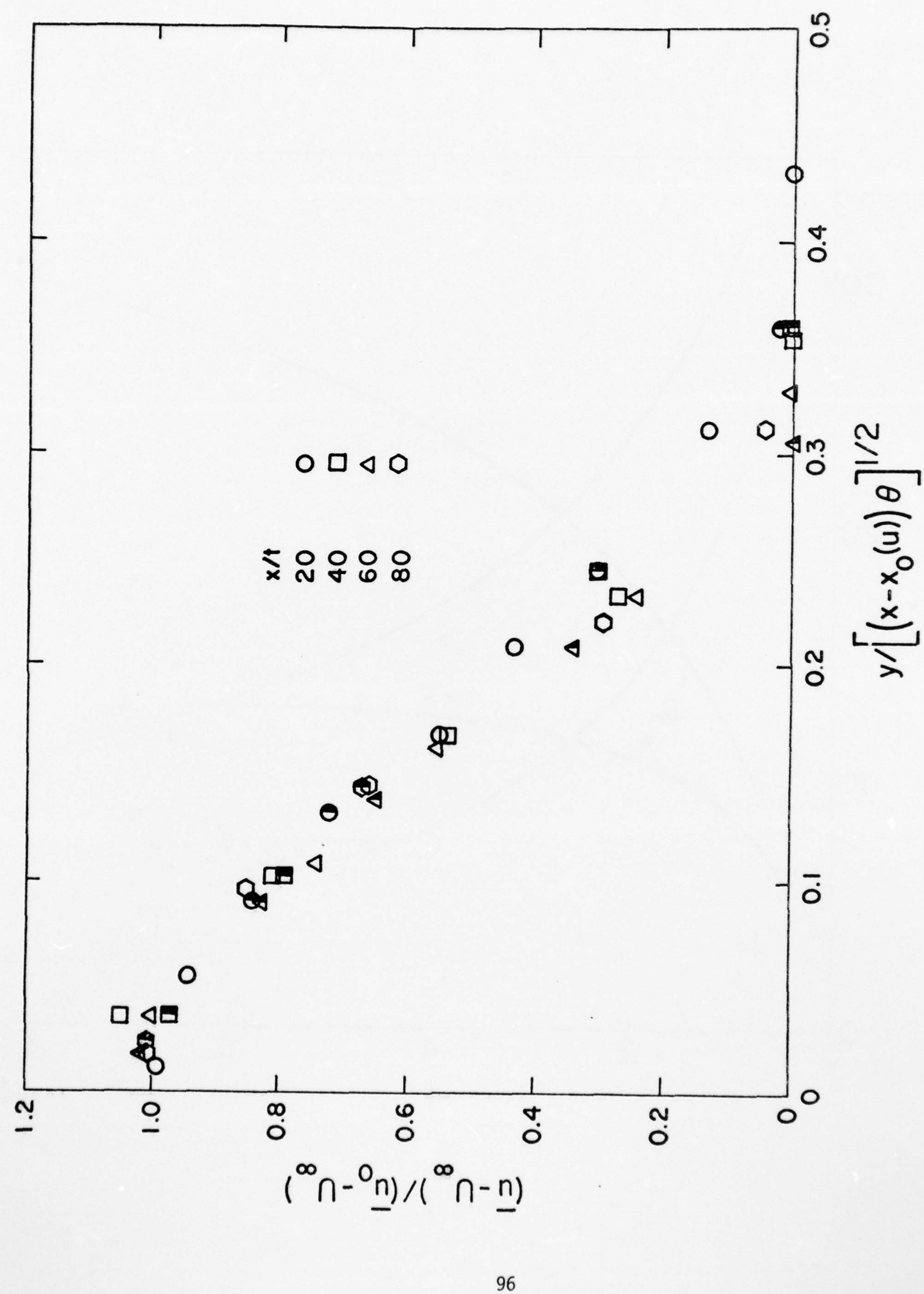

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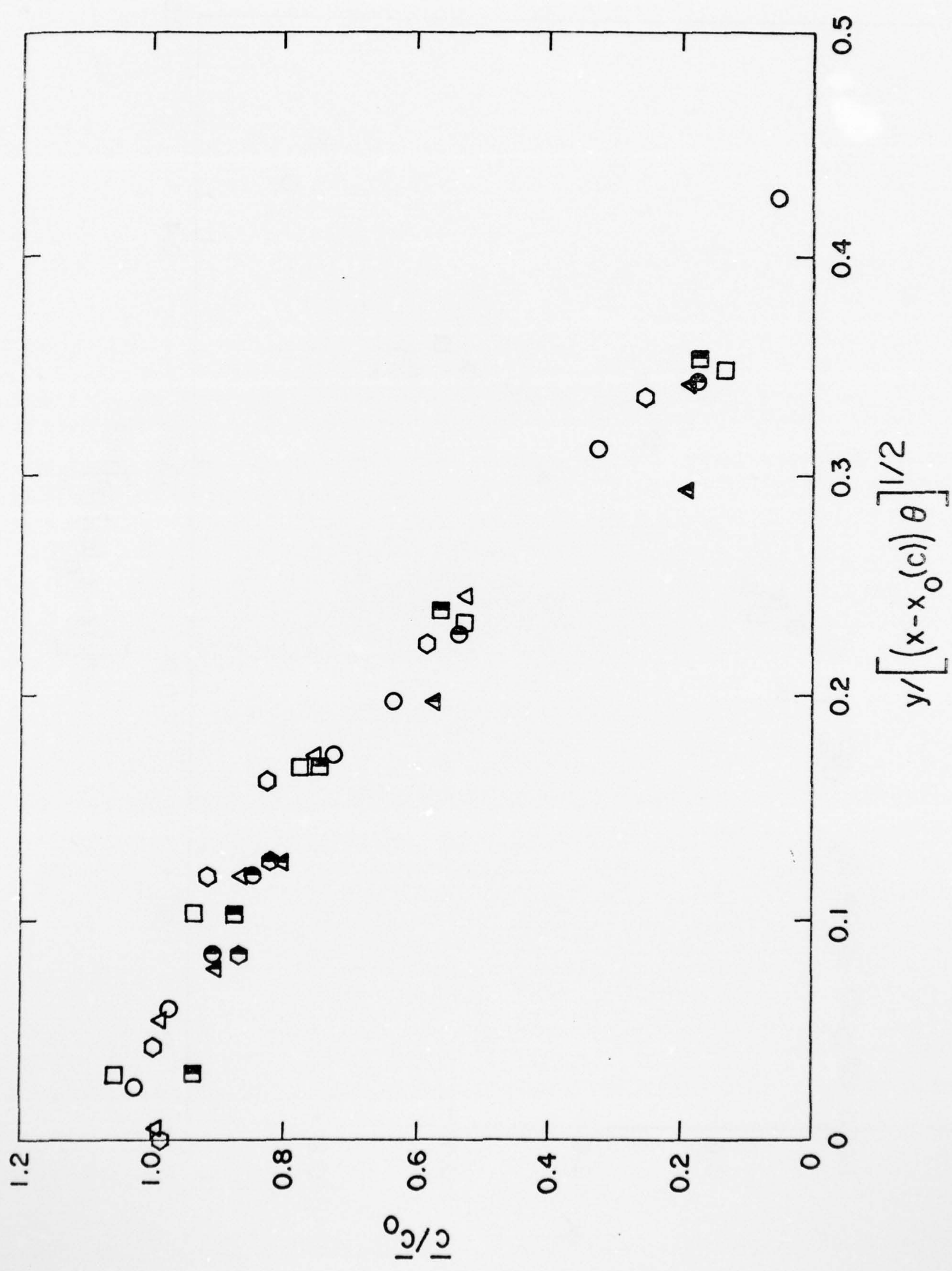

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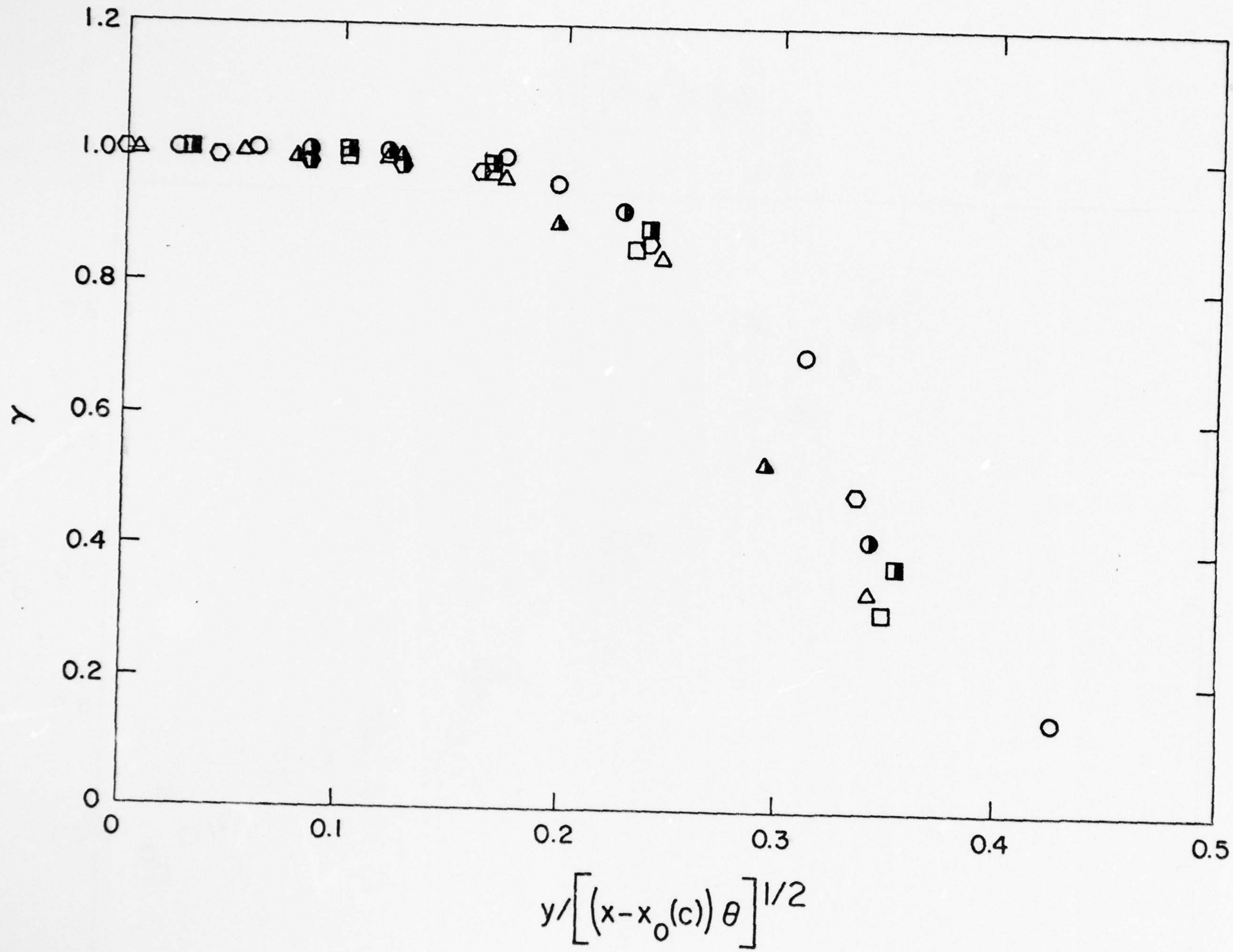
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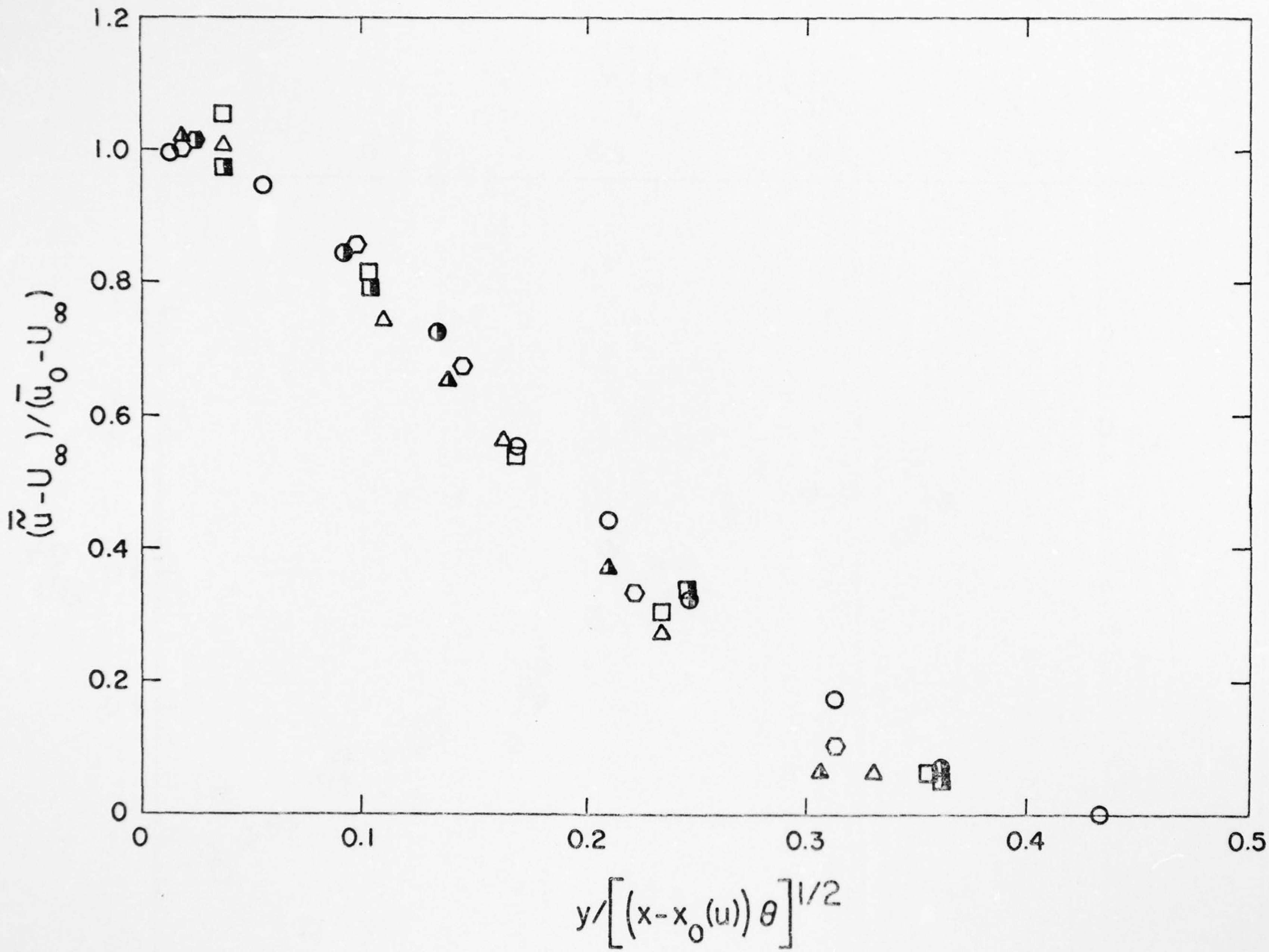

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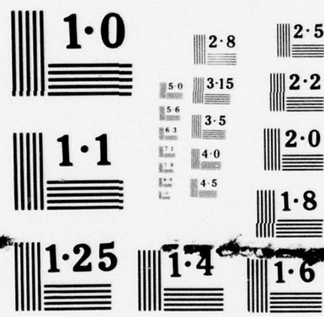

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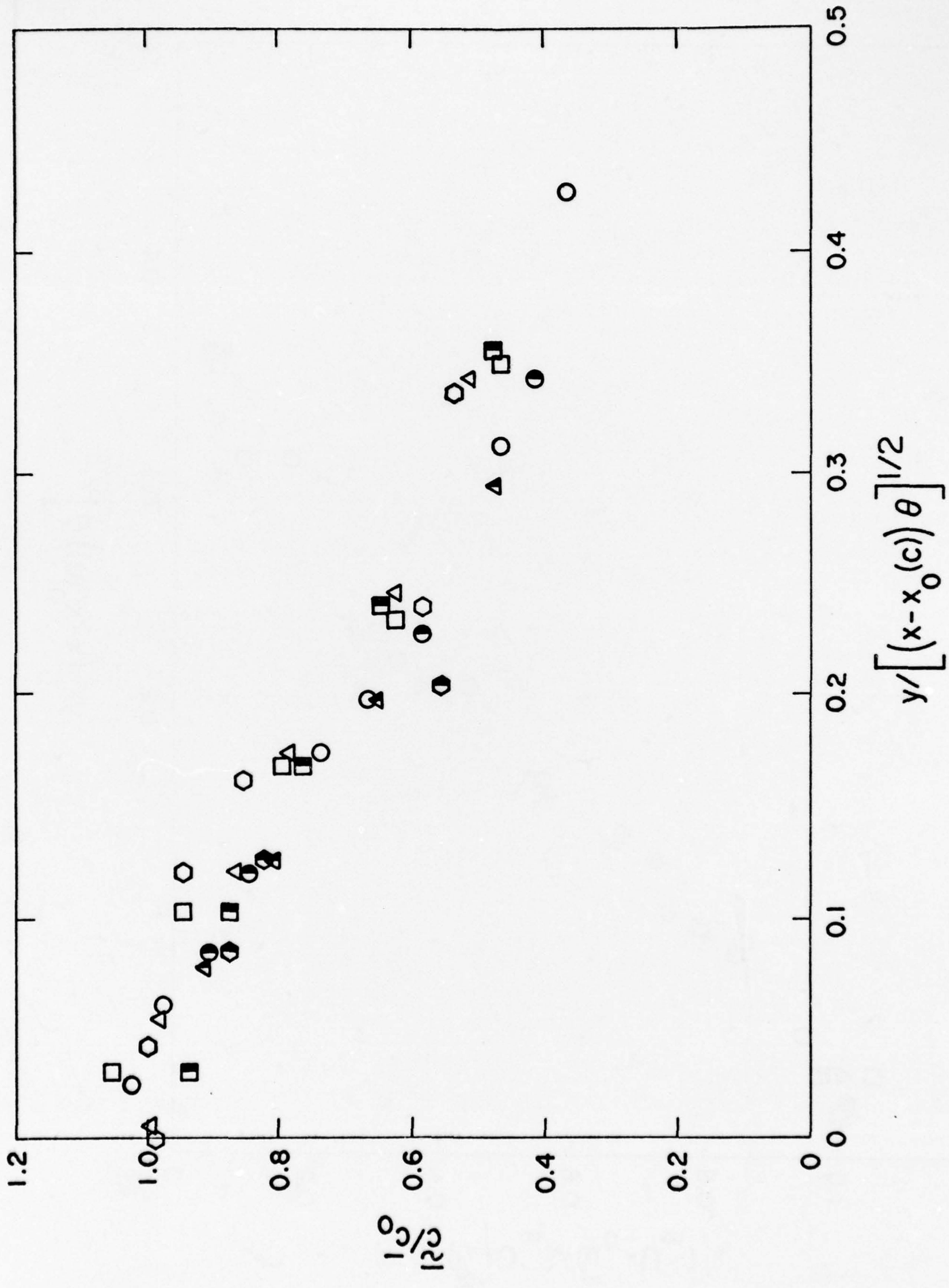

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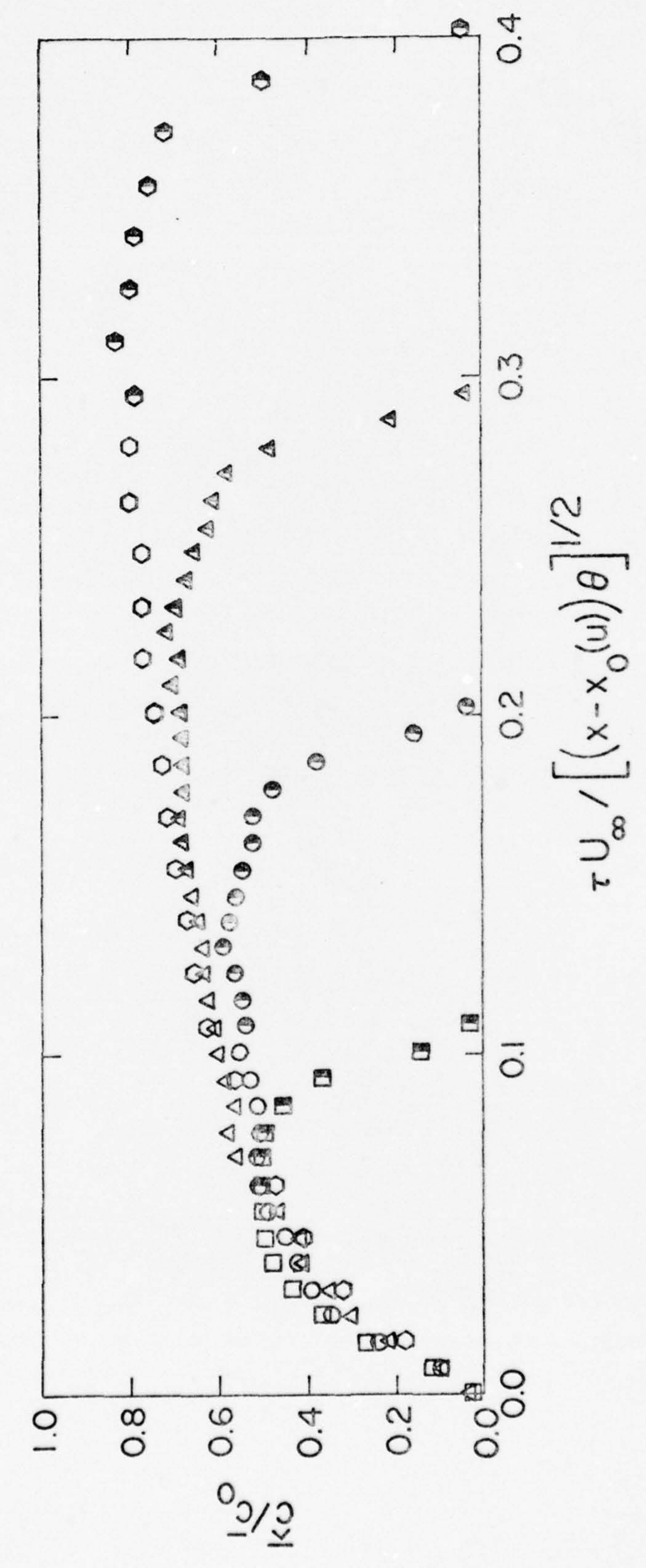

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RESEARCH ON TURBULENT MIXING

California Institute of Technology, Pasadena, California
Subcontract No. 8960-1

Professor A. Roshko, Principal Investigator
Dr. P. E. Dimotakis, Co-Investigator
Dr. Garry L. Brown*
Mr. John H. Konrad**
Mr. Luis P. Bernal, Research Assistant

Introduction

The objective of this research is to obtain a better understanding of the turbulent mixing processes that occur in mixing layers between gas streams of different velocities and densities. Such mixing layers are often a basic element in flows which occur in propulsive devices; examples of problems to which the research is relevant include turbulent combustion, jet noise, and thrust augmentation. The research has proceeded along two parallel lines. On the one hand, we have been making measurements of various statistical properties of the mixing region and their dependence on parameters such as Reynolds number, velocity ratio and density ratio. Such information provides important inputs for engineering models and calculation methods. On the other hand, we have been using the quantitative measurements, e.g., time- and space-resolved concentration measurements, together with flow visualization to identify and describe the physical processes occurring

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*On one-month leave from The University of Adelaide.

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in such mixing regions. Better understanding of the physics is important for the development of more realistic computing models and also for suggesting how turbulent mixing might be controlled or modified.

Discussion

Previous progress along the above lines included the measurement of intermittency, entrainment, mixedness factors and probability density functions for several values of the basic parameters (Ref. 1) and further descriptions of the physical properties of the large organized vortices which control the mixing layer (reviewed in Ref. 2). An additional result of this work, reported in Ref. 1, was the discovery of a critical Reynolds number above which mixing inside the turbulent layer is enhanced, apparently by the creation of secondary vortices. Much of the work of the past six months has been directed toward a better understanding of the phenomena connected with this change or transition. It is important because, besides its appreciable quantitative effect on the extent of mixedness in the turbulent region, it appears to be a key to understanding the development of three-dimensionality in the turbulence. The picture is not yet complete, but is roughly as follows:

1. Over a short range of Reynolds numbers centered at a value of about $\Delta U\delta/\nu = 2 \times 10^4$, there is an increase of mixedness as measured by a decrease in rms fluctuation of concentration, and as reflected in about 25% increase of reaction product calculated for a model reaction based on the inert mixing measurements.

2. No change in the mean spreading rate, or the profiles of mean velocity, density, shear stress, etc. occurs at this critical Reynolds number. We interpret this as indicating that there is no basic change in the large organized structures, which provide the main mechanism for the overall or gross mixing of the two streams.

3. Power spectral measurements of the concentration fluctuation show an increase of spectral content at high wave number, with no change at low wave numbers.

4. Shadow pictures showing simultaneous edge view and plan view of the mixing layer suggest that above the critical Reynolds number there exists a family of longitudinal vortices, in the streamwise direction, which are superimposed on the main large structures. They are thought to be of the Taylor type, the result of a secondary instability connected with radial variation of vorticity in the main two-dimensional structures. We have been making an effort to describe a self-consistent physical picture of their topology and the corresponding critical Reynolds number. While this interpretation of the physical events at the critical Reynolds number seems plausible, it is still speculative, and other measurements are needed to fill out the picture. Therefore, we have been developing hot wire instrumentation for attempting to measure velocity fluctuations in the mixing layer, in the same apparatus in which the previous observations were made. This is not quite straightforward because of the special nature of the apparatus, which was designed for short duration runs. The objective is to determine how the changes at the critical Reynolds number affect the turbulent intensities. Specifically, it is expected that an increase in $\overline{w'^2}$, the spanwise component, should accompany the appearance of longitudinal vorticity; it would give a

measure of the strength of the vorticity.

In preparation for another attack on the question of three-dimensionality, the LDV system is being adapted to two-channel operation. This will be used for making measurements of velocity at two spanwise points in a mixing layer in a water channel (cf. Ref. 3) and comparing them with simultaneous flow visualizations.

Other activity included further study of motion pictures of the mixing layer. These tend to reaffirm the idea that growth of the layer occurs mainly by coalescence of vortices. Examination of cases of particularly long-lived vortices indicates that their diameters do not increase appreciably during their lifespans.

References 2 and 3 appeared in print during this period.

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Semi-annual Progress Report, April 1, 1977

SWIRLING HEATED TURBULENT FLOWS AS RELATED TO COMBUSTION CHAMBERS

Project Squid

Mahinder S. Uberoi, Principal Investigator

We have theoretically analyzed slender line swirls and line vortices which have one velocity component U_θ , where θ is the direction of the swirl, r is the distance from the swirl axis, and t is the time. A line swirl has zero circulation for large radii, and a vortex has a finite circulation. The line swirl can be analyzed using conventional methods of analysis. The vortex is essentially a stable configuration, and we show that for long times turbulent vortices cannot exist.

Trailing swirls and trailing vortices have three velocity components U_θ (r,z) , U_z (r,z) , and U_r (r,z). Here the axial velocity difference between the core and the surroundings plays an important part: 1) it destabilizes the flow; 2) there is a radial flux of angular momentum associated with changing axial velocity; 3) the region over which the dynamic similarity exists is altered. In the studies of these flows, without exception, these effects have been neglected.

The claim that the vortex without axial velocity difference is essentially stable is substantiated by our experiments (Reference 1). We are using these experimental facts and physical ideas to develop a theory of swirling flows.

Although our major effort is concerned with flows without combustion, we are studying the types of flows and the <u>physical phenomena</u> associated with swirling combustion.

Combustible gas is ejected through a six-inch diameter swirling chamber with speeds up to 55 revolutions per second. This swirling chamber is contained in another chamber which can provide outside swirl. We are measuring mean and

fluctuating temperatures in these flames, which should provide a basis for the relevance of our work to swirling combustion. Our work is, of course, concerned with idealized problems.

One of our major tools for experimental investigation is the shooting hot wire probe which can simultaneously measure instantaneous temperature and velocity profiles. These measurements are more relevant to combustion studies than the conventional methods. We are using the probe to measure the structure of a two-dimensional heated jet. We have found that there are coherent structures in the initial region of the jet. There is considerable jitter associated with these structures, and we have used sound at proper frequencies to cut down the magnitude of this jitter. Our aim is to study this initial structure and its interaction with sound, since often in practice the jets are not long enough so that the initial structure is insignificant.

At the same time we want to study the universal characteristics of the turbulent-nonturbulent interface. As far as the combustion is concerned, a fluid particle is more influenced by the temperature rise across the surface separating the turbulent and nonturbulent flow than it is by the conventional mean or fluctuating temperature measurements. At the present time our shooting probe travels at a velocity of about 50 feet per second.

At one station across the jet the amount of fluid entrained fluctuates a great deal. Using simultaneous measurements of temperature and velocity we have found that the instantaneous mass flow in the turbulent core of the jet varies by a factor of two. There is, of course, fluid moving outside this turbulent core. Using our shooting probe, we hope to measure the instantaneous value of this flow.

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SECOND-ORDER CLOSURE MODELING OF TURBULENT COMBUSTION

Aeronautical Research Associates of Princeton, Inc.
Princeton, New Jersey
Subcontract No. 8960-26

Ashok K. Varma, Principal Investigator
Guido Sandri

Introduction

Turbulent flows involving chemical reactions occur in many combustion and propulsion devices such as gas turbine combustors, ram jets, rocket engines, chemical and gas dynamics lasers, etc. The interaction between the turbulent flowfield and the chemical reactions is important in many of these systems. It is important in determining combustion efficiency and pollutant formation as well as other combustion characteristics, such as ignition and extinction, flammability limits, combustion noise, etc. The basic objective of our research program under Project SQUID auspices is to analyze this interaction between chemistry and turbulence using a detailed and complete second-order closure analysis of turbulent reacting flows.

The use of such a higher-order closure procedure in reacting flows leads to the problem of development of suitable closure models for a number of third-order and higher-order scalar correlations that appear in the transport equations for the means and the second-order correlations. The procedure selected by us is to develop a model for the joint probability density function (pdf) for all the scalars involved in the flowfield. The model is called the A.R.A.P. "typical eddy" model and involves representing the pdf by a set of delta functions of variable strengths and positions in the scalar

phase space. The construction of the pdf uses all the available information from a second-order closure analysis of the flowfield.

A second-order closure computer program for turbulent reacting shear layers (RSL) has already been developed. The equations for the means and second-order correlations are derived from the time-averaged Navier-Stokes equations. The boundary layer approximations are used in these equations. The program uses fluid mechanical turbulence models developed by us and other investigators over the last two decades. The computer program is currently operational with a simplified "typical eddy" model and a "secondary" model for the scalar correlations. The simplified "typical eddy" model neglects the density moments in the construction of the model and, therefore, requires the solution of linear algebraic equations for defining the model at various points in the flowfield. In contrast, the complete model now being developed requires the solution of nonlinear algebraic equations. The "secondary" model simply sets all higher-order scalar correlations to zero. This model has been used for some recent calculations (Ref. 1) in hydrogen-air diffusion flames and DF chemical laser flows. The program is capable of handling multi-step reaction systems.

Discussion

The basic concept of the "typical eddy" pdf model, that is, the use of delta functions to model the continuous pdf that will exist in a turbulent reacting flow, was verified in our studies with the simplified model on low heat release reacting flows (Ref. 2). However, the neglect of the density correlations in the construction of the model was not satisfactory for problems involving exothermic reacting flows, and it was concluded very early in the beginning of the SQUID research program that the

more complete "typical eddy" model, including the density terms, has to be developed and used for these flows. The model as originally proposed (Ref. 3, 4) included the density correlations. However, as this requires the solution of a highly nonlinear system of equations, it was decided to develop the simplified model for the initial testing of the concept of the model. The second-order closure computer program that is already operational will be able to incorporate the complete "typical eddy" model, now being developed, with very minor changes.

During the past six months, we have completed the formulation of the nonlinear equations for the complete model. We have succeeded in obtaining analytical solutions for the equations for the two species constant temperature model. The formulation of the equations and the solution procedure are described in the Appendix. The solution is very promising for it shows that for any statistically consistent set of moments, we can find a rational solution for the model parameters, that is, the strengths of the delta functions are positive and their location is inside the physically realistic region of the scalar phase space. In this contract period we have also developed a computer program for the solution of the three species model equations and have tested the model to a limited extent. Further tests on the model are continuing. We are also developing the analytical solutions for the three species model.

During the remaining six months of the current contract period, we plan to complete the development of analytical and numerical solutions for the complete three species "typical eddy" model and to begin the process of incorporating the model into the second-order closure computer program. We will also incorporate the two species model into the program and begin some model testing by comparison of program results to recent experiments on two species mixing flows such as those reported by

the group at Caltech under Prof. Roshko and by Prof. Libby and his colleagues at UCSD.

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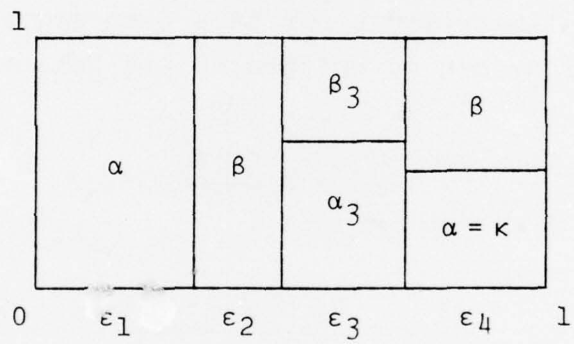
APPENDIX

The complete two species and the three species "typical eddy" models are shown in Figure 1. Only the species part of the joint pdf is shown here. There is also a corresponding structure for the enthalpy pdf as has been described earlier (Ref. 3,4). The two species model has 5 parameters, $\varepsilon_1 - \varepsilon_4$ and κ , and 5 moments, $\bar{\alpha}$, $\bar{\beta}$, $\overline{\alpha'\alpha'}$, $\overline{\alpha'\rho'}$, and $\overline{\rho'\rho'}$ to be used for their solution. For the three species model, there are 9 parameters, $\varepsilon_1 - \varepsilon_7$, κ_1 , and κ_2 , and these can be calculated from the 9 means and second-order correlations, $\bar{\alpha}$, $\bar{\beta}$, $\bar{\gamma}$, $\overline{\alpha'\alpha'}$, $\overline{\alpha'\beta'}$, $\overline{\beta'\beta'}$, $\overline{\alpha'\rho'}$, $\overline{\beta'\rho'}$, and $\overline{\rho'\rho'}$. The procedure is illustrated below for the two species system.



defining,

$$\Delta = 1 - \frac{W_\beta}{W_\alpha} \qquad 0 < \Delta < 1$$

$$s = \frac{\rho}{W_\beta \bar{p}/R\bar{T}} \qquad p' = 0$$

$$T' = 0$$

we obtain the following nonlinear equations by matching the model moments to the 5 moments obtained from the solution of the transport equations for the correlations.

$$\varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4 = 1$$

$$\varepsilon_1 + \alpha_3\varepsilon_3 + \kappa \cdot \varepsilon_4 = \bar{\alpha}$$

$$\varepsilon_1 + \alpha_3^2 \cdot \varepsilon_3 + \kappa^2 \cdot \varepsilon_4 = \overline{\alpha^2}$$

$$\left(\frac{1}{1-\Delta}\right)\varepsilon_1 + \left(\frac{\alpha_3}{1-\Delta\alpha_3}\right)\varepsilon_3 + \left(\frac{\kappa}{1-\Delta\kappa}\right)\varepsilon_4 = \overline{s\alpha}$$

$$\left(\frac{1}{1-\Delta}\right)^2 \varepsilon_1 + \left(\frac{1}{1-\Delta\alpha_3}\right)^2 \varepsilon_3 + \left(\frac{1}{1-\Delta\kappa}\right)^2 \varepsilon_4 = \overline{s^2}$$

These nonlinear equations have been solved in closed form, and the solutions can be written in the following form.

$$\varepsilon_i = C_i \frac{\kappa - \kappa_i^*}{D_i}$$

$$\kappa = \frac{N_1 + \alpha_3 N_2 + \alpha_3^2 N_3}{P_1 + \alpha_3 P_2 + \alpha_3^2 P_3}$$

where N_i and P_i are functions of the 4 moments.

$$C_i = C_i\left(\bar{\alpha}, \overline{\alpha^2}, \overline{s\alpha}, \overline{s^2}, \alpha_3\right)$$

$$\kappa_i^* = \kappa_i^*\left(\bar{\alpha}, \overline{\alpha^2}, \overline{s\alpha}, \overline{s^2}, \alpha_3\right)$$

$$D_1 = 1 - \kappa \qquad D_2 = \kappa$$

$$D_3 = \kappa - \alpha_3 \qquad D_4 = \kappa\left(1-\kappa\right)\left(\kappa - \alpha_3\right)$$

A considerable amount of effort has been devoted to obtaining the correct statistical bounds on the correlations $\bar{\alpha}$, $\overline{\alpha^2}$, $\overline{s\alpha}$, and $\overline{s^2}$. The strictest bounds that have been obtained are listed below.

$$0 \le \bar{\alpha} \le 1$$

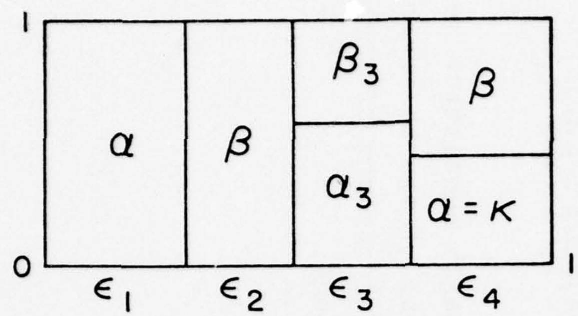
$$\bar{\alpha}^2 \le \overline{\alpha^2} \le \bar{\alpha}$$

$$\frac{\bar{\alpha}^2}{\bar{\alpha} - \Delta\overline{\alpha^2}} \le \overline{s\alpha} \le \frac{1}{1-\Delta} \, \frac{\bar{\alpha}(1-\bar{\alpha}) - \Delta(\bar{\alpha} - \overline{\alpha^2})}{(1-\bar{\alpha}) - \Delta(\bar{\alpha} - \overline{\alpha^2})}$$

$$1 + \Delta \cdot \overline{s\alpha} + \frac{\Delta}{\bar{\alpha}} \, \overline{s\alpha}^2 \le \overline{s^2} \le (1 + \Delta\overline{s\alpha})\frac{2-\Delta}{1-\Delta} - \frac{1}{1-\Delta}$$

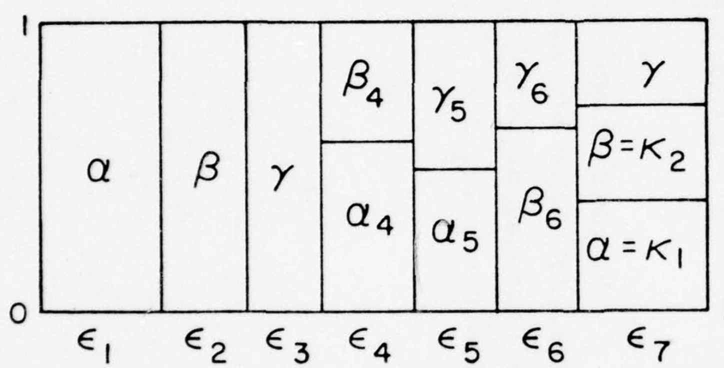
We have shown that for any statistically consistent set of moments, that is, moments within the limits of the above bounds, a rational solution for the strengths and locations of the delta functions ($\varepsilon_i \ge 0$, $0 \le \kappa \le 1$) can be found.

Two Species Model



$1,\ \bar{\alpha},\ \overline{\alpha'\alpha'},\ \overline{\alpha'\rho'},\ \overline{\rho'\rho'}$

Three Species Model



$1,\ \bar{\alpha},\ \bar{\beta},\ \overline{\alpha'\alpha'},\ \overline{\alpha'\beta'},\ \overline{\beta'\beta'}$

$\overline{\alpha'\rho'}\ \ \overline{\beta'\rho'}\ \ \overline{\rho'\rho'}$

Figure 1. Two and three species complete "typical eddy" models.

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Technical Reports

SQUID TECHNICAL REPORTS ISSUED SINCE 1 OCTOBER 1976

NUMBER	TITLE AND AUTHOR	DATE
PU-R3-76	Reporting Procedure by Project Squid Headquarters.	October 1976
UMO-1-PU	A Shock Tube Study of the Recombination of Carbon Monoxide and Oxygen Atoms, by Anthony M. Dean and Don C. Steiner.	October 1976
UTRC-4-PU	Applicability of Laser Raman Scattering Diagnostic Techniques to Practical *Combustion* Systems, by Alan C. Eckbreth.	November 1976
CIT-8-PU	An Experimental Investigation of Mixing in Two-Dimensional Turbulent Shear Flows with Applications to Diffusion-Limited Chemical Reactions, by John H. Konrad.	January 1977
MICH-16-PU	Transonic Flow Problems in Turbomachines, Proceedings of a Workshop held at Monterey, California, February 1976. Eds. T. C. Adamson, Jr., and M. F. Platzer.	March 1977
TRW-9-PU	The Coherent Flame Model for Turbulent Chemical Reactions by Frank E. Marble and James E. Broadwell.	February 1977
SMU-2-PU	Laminarescent Turbulent Boundary Layers: Experiments in Nozzle Flows, by R. L. Simpson and C. R. Shackleton.	February 1977
PIB-34-PU	Temperature, Concentration Velocity and Turbulence Measurements in Jet and Flames, by S. Lederman, A. Celentano and J. Glaser	March 1977

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Reports of progress during the past six months on the 23 research programs comprising Project SQUID are presented. The research programs fall into the areas of Aerodynamics and Turbomachinery, Combustion and Chemical Kinetics, Measurements and Turbulence. Project SQUID is a cooperative program of basic research related to jet propulsion. It is administered by Purdue University and sponsored by the Office of Naval Research.